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PETROLOGY FOR STUDENTS

AN INTRODUCTION TO THE STUDY OF ROCKS UNDER THE MICROSCOPE

BY

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PREFACE TO FIFTH EDITION

THE following work, now offered in a further revised edition, has been written to serve as a guide to the study of rocks in thin slices, and is of course assumed to be supplemented throughout by demonstrations on actual specimens Since it is designed primarily for the use of English-speaking students, examples are chosen, so far as is possible, from British, Colonial, and American rocks; and indeed the researches of British petrologists have now made it possible to illustrate almost all the leading rock-types from our own country. References to published descriptions are given in foot-notes.

No systematic account is given of the crystallographic and optical properties of minerals. This is rendered unnecessary by such books as Iddings' *Rock-Minerals* and other well-known works. In particular, I have made no explicit reference to the use of convergent light.

A number of new figures have been added for the present edition, and a few of the old ones have been withdrawn. Those given have been chosen mainly to illustrate typical rock-structures. Photographs and coloured plates of rock-slices may be sought in larger works, some of which are mentioned below.

A. H.

St John's College, Cambridge.
May, 1919.

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ABBREVIATIONS.

Amer. J. Sci. = American Journal of Science.

G.M. = Geological Magazine.

Journ. Geol. = Journal of Geology (Chicago).

Min. Mag. = Mineralogical Magazine.

Q.J.G.S. = Quarterly Journal of Geological Society.

CHAPTER I

INTRODUCTION

In this chapter will be included some notes on the optical properties of minerals, which may be of use to a novice; but there will be no attempt to supersede the use of books dealing systematically with the subject.

Microscope. We shall assume the use of a microscope specially adapted for petrological work, and therefore fitted with polarizing and analysing prisms, rotating stage with graduated circle and index, and 'cross-wires' of spider's web properly adjusted in the focus of the eye-piece. The sub-stage mirrors attached to such instruments usually have a flat and a concave face. With day-light the flat face should be used; with artificial light things should be so arranged that the mirror, used with the concave face, gives as nearly parallel rays as possible.

A double nose-piece, to carry two objectives, is very useful, although it usually gives very imperfect centring for high powers. The most useful objectives are a 1 inch or $1\frac{1}{2}$ inch and a $\frac{1}{4}$ inch, but for many purposes a $\frac{1}{8}$ inch is also very desirable. For minute objects, such as the 'crystallites' in glassy rocks and the fluid-pores in crystals, a high power is indispensable, and for very fine-textured sedimentary rocks an immersion-lens offers great advantages.

A selenite-plate, a quartz-wedge, and other special pieces of apparatus will be of use for various purposes. The methods involving their use may be found in the mineralogical text-books; where too the student will find guidance as to the examination of crystal-slices by convergent light.

Form of section of a crystal and cleavage-traces. A well-formed crystal gives in a thin slice a *polygonal section*, the nature of which depends not only upon the forms present on the crystal, but also on the direction of the section and on

its position in the crystal, as, *e.g.*, whether it cuts through the centre or only truncates an edge or corner. Again, the same shape of section may be obtained from very different crystals. Nevertheless, if several crystals of one mineral are present in a rock-slice, we can by comparison of the several polygonal sections obtain a good idea of the kind of crystal which they represent. Further, if by optical or other means we can determine approximately the crystallographic direction in which a particular crystal is cut, we can usually ascertain what faces are represented by the several sides of the polygon.

For this purpose we may require to measure the angle at which two sides meet, and this is easily done with a microscope provided with a rotating stage and graduated circle. Bring the angle to the intersection of the cross-wires, adjust one of the two sides to coincide with one of the cross-wires, and read the figure at the index of the circle. Then rotate until the other side is brought to coincide with the same cross-wire, and read the new figure. The angle turned through is the angle between the two sides of the section.

This angle is the same as that between the corresponding faces of the crystal, only provided the plane of section cuts these two faces perpendicularly. For a section nearly perpendicular to the two faces, however, the error will not be great.

In consequence of the mechanical forces which affect rock-masses, and also as a result of the process of grinding rock-slices, the minerals often become more or less fractured or even shattered. In a strictly homogeneous substance the resulting cracks are irregular; but if there be directions of minimum cohesion in crystals (cleavage), the cracks will tend to follow such directions, and will appear in a thin slice as fine parallel lines representing the *traces of the cleavage-planes* on the plane of section. The regularity and continuity of the cracks give an indication of the degree of perfection of the cleavage-structure; but it must also be borne in mind that a cleavage making only a small angle with the plane of section will, as a rule, not be shown in a slice.

In the case of a mineral like augite or hornblende, with two directions of perfect cleavage, the angle which the two

sets of planes make with one another is, of course, a specific character of the mineral, or at least characteristic of a group of minerals, such as the pyroxenes or the amphiboles. In a slice perpendicular to both the cleavages the traces will show the true angle. For any other direction of section the angle between the cleavage-traces will be different; but it will not vary greatly for slices nearly perpendicular to both the cleavages, and will often suffice for discrimination, as for instance between the 87° of the pyroxenes and the $55\frac{1}{2}°$ of the amphiboles. In a slice parallel to the intersection of the two cleavages the two sets of cleavage-traces reduce to one, and a slice of a mineral such as augite or hornblende which exhibits but one set of cleavage-traces may be assumed to be nearly parallel to the intersection of the cleavages.

A mineral not possessing any good cleavage often shows irregular cracks in rock-slices (*e.g.* quartz and usually olivine). This is especially the case in brittle minerals.

Transparency, colours, and refractive indices of minerals. Only a few rock-forming minerals remain opaque even in the thinnest slices: such as graphite, magnetite, pyrites, and pyrrhotite; usually hæmatite, ilmenite, limonite, and kaolin; sometimes chromite or picotite. These should always be examined in reflected light: the lustre and colour, combined with the forms of the sections and sometimes the evidence of cleavage, will usually suffice to identify any of these minerals. The great majority of rock-forming minerals become transparent in thin slices. Those which seen in hand-specimens of rocks appear opaque are often strongly coloured in slices, while those which in hand-specimens show colours are frequently colourless in thin slices. In the case of many minerals these 'absorption-tints' are thoroughly characteristic; but still more so are the differences of colour (pleochroism) in one and the same crystal according to the direction of the slice and the direction of vibration of a polarized beam traversing it, as noticed below.

The colours ascribed to minerals in the following pages and the epithet 'colourless' apply to thin slices of the minerals.

Apart from colour, the aspect of a mineral as seen in thin

slices by natural light varies greatly according to its *refractive index*[1], and it is of great importance for the student to learn to appreciate at a glance the effects due to a high or a low refractive index.

If a thin slice of a single crystal be mounted by itself in some medium of the same colour and refractive index as the crystal, its boundaries and surface-characters will be invisible, while its internal structure may be studied to the best advantage. Quartz mounted in Canada balsam (both colourless and of very nearly the same refractive index) is almost invisible. If olivine, a colourless mineral of much higher refractive index, be mounted in balsam, its boundaries and the slight roughness of its polished surface will be very apparent. In ordinary rock-slices, mounted in balsam, a roughened or 'shagreened' appearance may be taken as the mark of a mineral having a refractive index considerably higher than that of the medium used.

Again, a highly refringent mineral surrounded in the slice by others less highly refringent is seen to be more strongly illuminated than these, and its brightness is made more conspicuous by a dark boundary which is deeper in proportion to the difference in refractive index between the mineral in question and its surroundings. For these reasons a highly refringent crystal seems to stand out in relief against the rest of the slice.

Such considerations must be borne in mind in examining the minute inclusions in which many crystals abound. These inclusions may be of gas, of liquid (usually with a gaseous bubble), of glass, or a crystal of some other mineral; and these may be distinguished by observing that the depth of the dark border depends upon the difference in refractive index between the enclosing and the enclosed substance. The most strongly marked border is seen when a gaseous is enclosed by a solid

[1] By this must be understood its *mean* refractive index. A crystal of any system other than the regular has in any section two refractive indices, the magnitudes of which depend further upon the direction of the section; but these differences in any one mineral are usually small as compared with the differences between the mean indices in different minerals.

substance. A liquid-inclusion in a crystal has a less marked boundary, but a bubble of vapour in the liquid is strongly accentuated. A glass-inclusion is still less strongly marked off from its enclosing crystal, while a gas-bubble contained in it shows a very deep black border.

When two minerals (or a mineral and Canada balsam) are in contact with one another in a thin slice in such a position that their surface of junction is cut approximately at right angles by the plane of section, it is easy to determine which of the two has the higher refractive index. For this purpose the illumination should be limited by a diaphragm placed below the stage, and a high-power objective focussed upon the line of junction at the upper surface of the slice. This line is then seen to be bordered by a narrow bright band on the side of the more highly refringent mineral and a narrow dark band on the other side. If the objective be depressed until the lower surface of the slice is in focus, these appearances are reversed.

The refractive indices of the several rock-forming minerals may be found in the tables or books of reference, but the student will find it useful to carry in his mind such a list as that given below.

Refractive indices of the common rock-forming minerals.

Very low (1·43–1·51): tridymite, sodalite, analcime and most other zeolites, (volcanic glasses), leucite. 1.54

Low (1·52–1·63): felspars, nepheline, quartz, (Canada balsam), micas, calcite, dolomite, wollastonite, actinolite, melilite.

Moderate (1·63–1·645): apatite, tourmaline, andalusite, hornblende.

High (1·68–1·8): olivine, sillimanite, pyroxenes, zoisite, idocrase, epidote, garnets.

Very high (1·9–1·95): sphene, zircon.

Extremely high (2·0–2·7): chromite, rutile.

Extinction between crossed nicols. When the polarizing and analysing Nicol's prisms are used together, with their planes of vibration at right angles to one another

('crossed nicols')[1], if no object be interposed, there is total darkness ('extinction'); and the same is the case when a slice of any vitreous substance, such as obsidian, is placed on the stage. If, however, a slice of a crystal of any system other than the regular be interposed, there is in general more or less illumination transmitted, often with bright colours. On rotating the stage[2] carrying the object, it is found that extinction takes place for four positions during a complete rotation, these being at intervals of a right angle. In other words, there are two *axes of extinction* at right angles to one another, and the slice remains dark only while these axes are parallel to the planes of vibration of the nicols, which are indicated by the cross-wires in the eye-piece. If we rotate the slice into a position of extinction and then remove the nicols, the cross-wires will mark the axes of extinction in the crystal-slice.

Without attempting to deal fully with this branch of physical optics, we may remark that all the optical properties of a crystal are related to three straight lines conceived as drawn within the crystal at right angles to one another (the *axes of optic elasticity*) and to a certain ellipsoid having these three straight lines for axes (the *ellipsoid of optic elasticity*). The positions of the three axes may vary in different minerals, but they must always conform with the symmetry proper to the system, and the same is true of the relative lengths of the axes of the ellipsoid. The plane of section of any slice cuts the ellipsoid in an ellipse, the form and position of which depend upon the direction of the section (*ellipse of optic elasticity*), and the axes of extinction are the axes of this ellipse.

In certain cases the ellipse of optic elasticity may be a circle. For this any diameter is an axis, and accordingly we find that such a slice gives extinction throughout the complete

[1] In using the two Nicol's prisms, it should always be ascertained that they are crossed. For this purpose the rotating prisms are usually provided with catches in the proper positions, but the true test is total darkness when no object is interposed.

[2] In some microscopes, such as that devised by Mr A. Dick, the stage is fixed, and the two nicols rotate, retaining their relative position, an arrangement with several advantages. We shall assume for distinctness that the stage is made to rotate, as in the most usual models.

rotation. In crystals of the triclinic, monoclinic, and rhombic systems there are two directions of section which give this result. They are perpendicular respectively to two straight lines in the crystal (the *optic axes*), which lie in the plane of two of the axes of optic elasticity, and are symmetrically disposed towards them. In crystals of the tetragonal and rhombohedral systems the two optic axes coincide with one another and with the unique crystallographic axis, and only slices perpendicular to this give total darkness. In the regular system, the ellipsoid being a sphere, the ellipse is always a circle, and all slices give total darkness between crossed nicols.

Crystals of the regular system are spoken of as singly refracting or optically isotropic, and their optical properties[1] are similar to those of a glassy or colloid substance. Crystals of the other systems are doubly refracting or birefringent, and they are divided into uniaxial and biaxial according as they have one or two optic axes.

It is evident that the chance of a slice cut at random from a birefringent crystal being perpendicular to an optic axis is very small. If more than one crystal of a given mineral be present in a rock-slice, and all remain perfectly dark between crossed nicols throughout a rotation, it is a safe conclusion that the mineral is a singly refracting one.

Straight and oblique extinction. By bearing in mind that the ellipsoid of optic elasticity, and consequently all the optical properties of a crystal, must conform with the laws of symmetry proper to the crystal-system of the mineral, we can foresee all the important points as regards the position of the axes of extinction in crystals of the different systems cut in various directions. For instance, a longitudinal section of a prism of apatite (a hexagonal mineral) will extinguish when its length is parallel to either of the cross-wires: this is *straight extinction*. A longitudinal section of a prism of albite (a triclinic mineral) will, on the other hand, have axes of extinction inclined at some angle to its length: this is *oblique extinction*. It is to be noticed that these terms have no meaning

[1] That is, such of them as we are here concerned with.

unless it is stated or clearly understood from what direction in the crystal the obliquity is reckoned. In these examples we reckoned with reference to one of the crystallographic axes, defined by the traces of known crystal-faces. Another character often utilised is the cleavage. Thus in a monoclinic mineral with prismatic cleavages, such as hornblende, we select a crystal so cut that the two cleavages give only one set of parallel traces. These traces are then parallel to one of the crystallographic axes (the vertical axis), and we examine the position of extinction with reference to this. First we bring the cleavage-traces parallel to one of the cross-wires, removing if necessary for this purpose one or both of the nicols, and note the figure indicated on the graduated circle. Then, with crossed nicols, we rotate until the crystal becomes dark, and again note the figure. The angle through which we have turned is the *extinction-angle*. Observe that if a rotation through, say, 15° in one direction gives extinction, a rotation through 75° in the opposite direction would have given the same. For most purposes we do not need to distinguish between the two directions of rotation, but take merely the smaller of the two angles.

To obtain a measurement of use in identifying a mineral we require more than the above. Slices of a crystal of hornblende cut in various directions along the vertical axis will give different extinction-angles, from zero (straight extinction) in a section parallel to the orthopinacoid to a maximum value in a certain other section. This *maximum extinction-angle* is a specific character, being nearly the angle between the vertical crystallographic axis and the nearest axis of optic elasticity. We may determine it with sufficient accuracy for most purposes by noting the extinction-angles in two or three vertical sections of the same mineral in a rock-slice and taking the largest value obtained.

By attention to the following points it is in most cases possible to refer to its crystal-system an unknown mineral of which several sections are presented in a rock-slice:

Regular system: singly refracting; all slices extinguish completely between crossed nicols, as in glassy substances.

Tetragonal and Rhombohedral (including Hexagonal): birefringent and uniaxial; straight extinction for longitudinal sections of crystals with prismatic habit and for any cross-sections of crystals with tabular habit. The two systems cannot be distinguished from one another by optical tests, but in cross-sections of prisms the crystal outline or cleavages will usually suffice to discriminate.

Rhombic (this and the remaining systems birefringent and biaxial): straight extinction for longitudinal sections of crystals with prismatic habit; sections perpendicular to the vertical axis have axes of extinction parallel to pinacoidal faces or cleavages and bisecting the angles between the traces of prism-faces or prismatic cleavages. A section *nearly* parallel to the vertical axis will give *nearly* straight extinction, except in minerals (*e.g.* hypersthene) which have a wide angle between the optic axes.

Monoclinic: two important types may be noticed according as the intersection of the chief cleavages (and direction of elongation of the crystals) lies in or perpendicular to the plane of symmetry. In the former case longitudinal sections may give any extinction-angle from zero up to a maximum value characteristic of the species or variety: in the latter (*e.g.* epidote and wollastonite) longitudinal sections give straight extinction. The former case is the more frequent.

Triclinic: no sections give systematically straight extinction.

Twinning. The existence of twinning in a slice of a crystal is, in general, instantly revealed by an examination of the slice between crossed nicols, since the two individuals of the twin show different interference-tints, and extinguish in different positions[1] (fig. 3, *B*). When twin-plane and face of association coincide—the most common case—a slice perpendicular to the twin-plane will give in the two individuals of the twin extinction-angles which, reckoned from the line of junction, are equal but in opposite directions. Conversely, a crystal

[1] The only exceptions (apart from opaque crystals) are in minerals, like the spinels, optically isotropic, and in cases in which the law of twinning is such that the directions of the axes of optical elasticity are not altered (*e.g.* quartz).

which gives equal but opposite extinction-angles may be assumed to be cut very nearly perpendicularly to the twin-plane. If the plane of section cut the twin-plane of a crystal at a very small angle, the two individuals of the twin will overlap for a sensible width, and we shall see between the two a narrow band which does not behave optically with either.

When repeated twinning occurs, as in felspars with albite-lamellation, the lamellæ divide, as regards optical behaviour, into two sets arranged alternately.

Extinction-angles in felspars. The discrimination of the several felspars by means of their extinction-angles measured on cleavage-flakes, as perfected by Schuster, is a method of great precision, but is not applicable to crystals in rock-slices. For these the method advocated by Michel Lévy and others will often be found useful. There are two cases in which it is readily applied.

(i) *For crystals with albite-lamellation*:—Select sections cut approximately perpendicular to the lamellæ. These are known by the extinction-angles in the two alternating sets of lamellæ, reckoned from the twin-line, being in opposite directions and nearly equal; also by the illumination of the two sets of lamellæ being not very different when the twin-line is parallel to a cross-wire. Measure the angles in question in three or four crystals so selected, and take the greatest value found. This will be very nearly the maximum angle for all such sections, which is a specific constant for each kind of felspar, as indicated for certain types in the annexed diagram (fig. 1). The values for types not given in the diagram may be judged with sufficient accuracy by interpolation, since the maximum extinction-angle changes steadily from one end of the series to the other. It will be noticed, however, that in certain cases different kinds of felspar (*viz.* those placed on the same vertical lines in the diagram) give equal angles, and in this connection two remarks are to be made.

(*a*) A slice of a crystal has two directions of extinction, at right angles to one another. Hitherto we have taken the angle to the nearest direction of extinction, but the diagram shows that for angles of 37° or more this introduces an ambiguity.

It is then necessary to distinguish between the two directions (by means of the quartz-wedge or some other contrivance) and to select that one which corresponds with the least axis of the ellipse of elasticity (indicated by an arrow-head in the diagram). In this way anorthite and bytownite are discriminated from the medium labradorites. Other criteria may sometimes be used, *e.g.* the stronger birefringence of anorthite, as pointed out below[1].

(*b*) The signs + and − denote angles measured in opposite directions crystallographically. Unless other means of discrimination can be made use of, we have usually no way of distinguishing the two directions, and there is consequently an ambiguity between albite and the more basic oligoclases (with oligoclase-andesine). Since the latter have about the same refractive index as quartz and Canada balsam, while the index for albite is distinctly lower, a discrimination may sometimes be made by rough observations of comparative refringence.

Summarily, we have the following characteristic angles for different felspars:—

0° to 5°, oligoclase, the more acid types.
6° to 16°, albite *and* the more basic oligoclases (with oligoclase-andesine).
16° to 22°, andesines.
27° to 45°, labradorites.
45° to 50°, bytownites.
50° and above, anorthites.

(ii) *For microlites*, assumed to have their length parallel to the intersection of the two principal cleavages:—Here we measure extinction-angles from the long axis of the microlites, and select the highest angle obtained by measurements on several microlites. The characteristic maxima for certain varieties of plagioclase are given in the annexed diagram (fig. 2), and the values for intermediate varieties can be interpolated. As before, there are two points to be noted.

[1] Another point worthy of notice is the frequency with which certain angles (less than the maximum) occur in a number of sections perpendicular to the albite-lamellæ. For anorthite the favourite angles are 32° and 41°, for medium labradorite 21° and 36°.

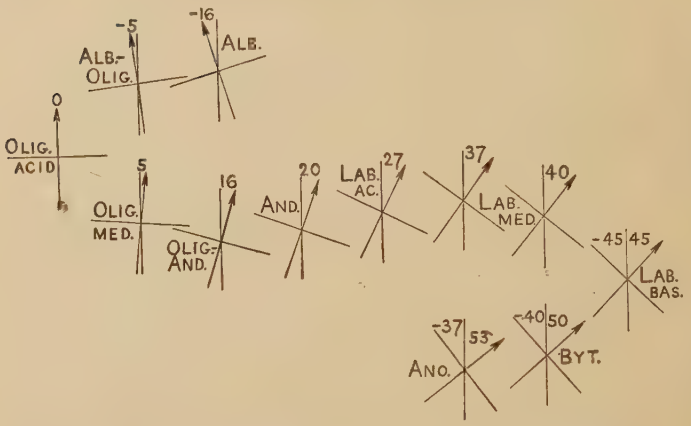

FIG. 1. MAXIMUM EXTINCTION-ANGLES OF PLAGIOCLASE FELSPARS IN SECTIONS AT RIGHT ANGLES TO THE ALBITE-LAMELLÆ.

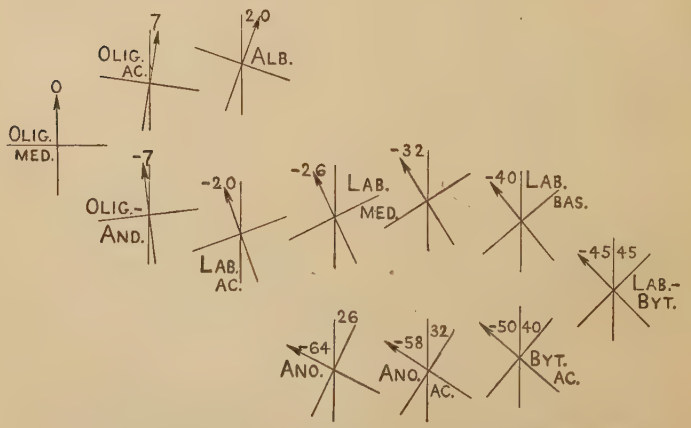

FIG. 2. MAXIMUM EXTINCTION-ANGLES OF PLAGIOCLASE FELSPARS IN LONGITUDINAL SECTIONS OF MICROLITES.

(*a*) If the angle of extinction as measured is 26° or more, we must discriminate by the quartz-wedge or otherwise between the two directions of extinction.

(*b*) If the angle is 20° or less, an ambiguity occurs which cannot be removed by this method; *viz.* between albite and andesine or andesine-labradorite and between acid oligoclase and oligoclase-andesine. There is thus more unavoidable ambiguity in this case than in that of albite-lamellæ, as appears from the following values for different felspars.

0° to 7°, oligoclase with oligoclase-andesine.
8° to 10°, albite-oligoclase *and* andesine.
10° to 20°, albite *and* andesine-labradorite with acid labradorite.
30° to 42°, labradorite, medium to basic.
49° to 56°, bytownites.
58° to 64°, anorthites.

Becker[1] has suggested another test applicable to microlites, which may very conveniently be used to supplement the above; since, although it is of little use for the more basic varieties, it affords a useful criterion for distinguishing the oligoclases, andesines, *etc.* Instead of longitudinal sections, perpendicular cross-sections of the microlites are selected. These are small, nearly square, and sharply defined. The extinction-angles vary from − 13° for pure albite to 42½° for anorthite, and from Becker's figures we may deduce the following approximate values:—

0° to 4°, oligoclase, acid.
4° to 7°, oligoclase, medium, *and* albite-oligoclase.
7° to 13°, oligoclase, basic, *and* albite.
18° to 22°, andesine.
26½° to 38°, labradorite, acid to medium.
38° to 42½°, medium labradorite to anorthite.

If the sections selected for measurement be as much as 10° from the true perpendicular cross-section, the resulting error is

[1] 18*th Ann. Rep. U.S. Geol. Sur.* Part III (1898), 32–34, and *A. J. S.* (1898) v, 349–354, pl. III. For a more general account of the modern optical methods of discriminating the felspars see Winchell, *Amer. Geol.* (1898) xxi, 12–48, pl. II–VIII, and Iddings, *Rock Minerals* (2nd ed. 1911).

only about $1\frac{1}{2}°$ to $2\frac{1}{2}°$ in the more acid half of the plagioclase series, and therefore does not vitiate the conclusion.

Zonary banding in felspars. In many rocks the felspars show between crossed nicols concentric zones roughly parallel to the boundary of the crystal, the successive zones extinguishing in different positions (fig. 3, *A*). (If there be albite-lamellation, we confine our attention to one of the two sets of lamellæ.) This difference in optical behaviour among the successive layers which build up the crystal may arise in two ways: firstly, from the successive zones being of different kinds of

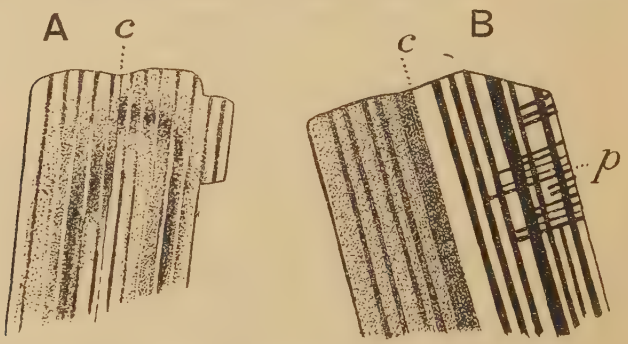

FIG. 3. PLAGIOCLASE CRYSTALS; ×14, CROSSED NICOLS.

A. Albite-lamellation combined with twinning on the Carlsbad law (*c*) and with strong zonary banding.

B. Pericline-twinning (*p*) in addition to albite and Carlsbad.

felspar-substance; or, secondly, from ultra-microscopic twinning affecting in various degrees the different layers of a crystal chemically homogeneous. This has been pointed out by Michel Lévy, and he gives a test which will resolve all except certain rare cases. It will be found, on rotating the slice between crossed nicols, that there are certain positions in which the albite-lamellæ disappear. If simultaneously with this the zonary banding disappears also, so that the whole crystal[1] is

[1] Or if there be Carlsbad-twinning also, the whole of one individual of the Carlsbad-twin.

uniformly illuminated, the appearances can be explained by ultra-microscopic twinning alone: if this is not the case, the zonary banding may be ascribed to the successive layers of felspar-substance in each crystal differing in chemical composition. When this occurs, the rule generally holds that the layers or zones become progressively more acid from the centre to the margin.

Interference-tints. We have remarked that a thin slice of a doubly refracting crystal, examined between crossed nicols, is in general not dark except when placed in certain definite positions. In any other position it does not completely extinguish the light, but its effect, in conjunction with the nicols, is partially to suppress the several components of the white light in different degrees, so that in the emergent beam these components are no longer in the proportions to give white light. In this way arise polarization-tints or interference-tints. These belong to a definite scale, known as *Newton's scale*, on which the several tints (though graduating into one another), are distinguished by names and divided into several 'orders.' The student should learn the succession of these tints, in the first place from the coloured plates accompanying some mineralogical works[1], but ultimately from the minerals themselves. The precise position in the scale of a given tint observed between crossed nicols can be fixed by means of a quartz-wedge[2] or other contrivance for 'compensating' or neutralising the birefringence of the slice; but for ordinary purposes, at least with colourless or nearly colourless minerals, the interference-tint can be judged by eye with sufficient accuracy. The most brilliant colours are those of the second order and at the top of the first; the lowest colours of the first order are dull greys;

[1] Michel Lévy and Lacroix, *Les Minéraux des Roches* (1888); Rosenbusch (transl. Iddings), *Microscopical Physiography of the Rock-making Minerals*; Iddings, *Rock Minerals* (2nd ed. 1911).

[2] The edge of the quartz-wedge is usually not thin enough to give the lowest tints of the scale. This can be remedied by means of a film of mica, properly oriented: see Mahony, *Nature*, 2 August, 1906, lxxiv, 317–318. On some special applications of the quartz-wedge see Evans, *Min. Mag.* (1905) xiv, 87–92. On the mica-wedge, which for many purposes affords an efficient substitute, see Dick, *Notes on a New Form of Polarizing Microscope* (1890).

while in the third and fourth orders the tints become brighter but paler, ultimately approximating to white.

The interference-tints given by a crystal-section depend (i) on the birefringence of the mineral, which is a specific character: (ii) on the direction of the section relatively to the ellipsoid of optic elasticity, the tint being highest for a section parallel to the greatest and least axes of the ellipsoid; (iii) on the thickness of the slice. These last two are disturbing factors, which must be eliminated before we can use the interference-tints as an index of the birefringence of the crystals, and so as a useful criterion in identifying the mineral.

The fact that the interference-tints depend in part on the direction of the section through the crystal will rarely be found to give rise to any difficulty in estimating roughly the birefringence of the mineral. If two or three crystals of the same mineral are contained in a rock-slice, it is sufficient to have regard to that one which gives the highest interference-tints. Even a single crystal will in the majority of cases give tints not so far below those proper to the mineral as to occasion error, but the possibility of the section having an unlucky direction must be borne in mind.

Rock-slices prepared by a skilful operator are in most cases so nearly constant in thickness that variations in this respect may be left out of consideration. Any important difference is at once detected by well-known minerals giving unusual interference-tints. Thus, if quartz or orthoclase give the yellow of the first order, the slice is rather a thick one; if they give orange or red, the slice is considerably thicker than the average of good preparations. Knowing this, we can make allowance for it in estimating the birefringence of some doubtful mineral in the same slice. Such allowance can be roughly judged, or it can be made with considerable precision by means of the large coloured plate of Michel Lévy and Lacroix[1].

The actual birefringence (numerically expressed) of the

[1] This plate can be purchased separately and mounted as a wall-diagram. On the method of using it see Pirsson and Robinson, *A. J. S.* (1900) x, 260–265; Joly, *Sci. Pr. Roy. Dubl. Soc.* (1901) ix (N.S.), 485–488.

several rock-forming minerals, and the interference-tints which they afford in slices of ordinary thickness, are given in numerous books and tables. For rough purposes the student will find it useful to remember about as much as is contained in the following table.

Birefringence and interference-tints of the commoner rock-forming minerals. (The colours given are for slices ·001 inch in thickness.)

Very weak (giving steel-grey tints): leucite, apatite, nepheline, melilite.

Weak (giving blue-grey to white of first order): zoisite, microcline, orthoclase, albite, oligoclase, andesine, labradorite, quartz, bytownite, enstatite.

Moderate (giving white, yellow, or orange of first order): andalusite, chlorite, anorthite, hypersthene.

Strong (giving red of first order to violet and blue of second): tourmaline, augite and diallage, common hornblende and actinolite.

Very strong (giving green, yellow, or orange of second order): olivine, epidote, talc, biotite, muscovite.

Extremely strong (giving the pale colours of the third and fourth orders to almost pure white): zircon, hornblende rich in iron, sphene, calcite and dolomite, rutile.

Note that in minerals with strong absorption, such as the deep-coloured micas and hornblendes, the interference-colours are more or less masked by those due to absorption.

Pleochroism. A character often useful in identifying minerals is pleochroism, the property of giving different absorption-tints for different directions of vibration of the light within the crystal. To observe this property, we use the lower nicol only, and rotate either it or the stage. The direction of vibration is that of the shorter diagonal of the nicol.

It is necessary not only to observe the changes of colour, if any, but also to note their relation to directions of vibration within the crystal. For example, elongated sections of biotite and hornblende, tourmaline and sphene, may be found to

change from a deeper to a paler tint of brown on rotation; but while in the first pair of minerals the direction of vibration most nearly coincident with the long axis of the section gives the deeper tone, in the second pair it gives the paler.

To be more precise, we wish to know, for a specification of the pleochroism of a given mineral, the absorption-tints for vibrations in three definite directions within the crystal—those of the three axes of optical elasticity. Taking a given mineral, say a hornblende, of which a number of crystals occur in our slice, we may proceed as follows. Select a crystal showing only one set of cleavage-traces and giving the maximum extinction-angle: this section will be approximately parallel to the plane of symmetry, and will contain two of the required axes. These axes are the axes of extinction for the section, and their positions are thus easily found. The one nearest to the cleavage-traces is the γ-axis, the other the α-axis. Bring the γ-axis to coincide in direction with the shorter diagonal of the nicol, adjusting the position by obtaining extinction, and then removing the upper nicol. Observe the colour: then do the same for the α-axis. For the remaining β-axis we must use another crystal. We may choose one showing only a single set of cleavage-traces and giving straight extinction: the β-axis is perpendicular to the cleavage-traces. Or we may choose a section showing two sets of cleavage-traces intersecting at a good angle and extinguishing along the bisectors of the angles between the cleavage-traces: the β-axis is the bisector of the acute angle.

Minerals of the rhombohedral and tetragonal systems can have only two distinct absorption-tints (*dichroism*), one for vibrations parallel to the longitudinal axis (extraordinary ray), the other for vibrations in any direction perpendicular to it (ordinary ray). In the regular system the absorption-colours are independent of direction.

In consequence of pleochroism the absorption-tints of a mineral vary in differently cut crystals seen in natural light, but the precise nature of the pleochroism can be investigated only with a polarized beam.

Examination of a rock-slice. In studying a rock-slice it is always well to proceed methodically. A low power

should first be used: any object which it is desirable to examine under a higher magnification should be brought to the centre of the field before the objective is changed for a higher power. The slice should always be observed first in natural light: by their outline, relief, cleavages, inclusions, alteration-products, *etc.*, all the ordinary rock-forming minerals can be identified in most cases without the use of polarized light. If the lower nicol is not readily movable it may be left in for many purposes; but it must be remembered that half the illumination is thus cut off, and for any but the lowest magnifying powers this is of importance. Opaque substances should always be viewed by reflected light.

To examine the pleochroism of any coloured constituent, we put in the lower nicol, and rotate either it or the stage. For verifying feeble pleochroism the former plan is preferable, but the nicol must be rotated until its catch holds it before proceeding to the use of the two nicols, which will be the next act.

For some purposes oblique illumination is advantageous. For instance, the extremely slender needles of apatite in certain lamprophyres and other rocks become visible only by this means. A 'spot-lens' may be improvised by placing beneath the stage a convex lens of short focal length with its central part covered by a disc of black paper.

In using a high power it will be noticed that the focus is very perceptibly different for the upper and lower surfaces of the slice. To make out the form of a body enclosed in the thickness of the slice the focus should be gradually moved, so as to bring different depths successively into view.

It cannot be too strongly insisted that the identification of the component minerals of a rock is only a part of the examination. The mutual relations of the minerals and their structural peculiarities must also be observed, the order of crystallization, intergrowths, interpositions, decomposition-products, pseudomorphs, *etc.*, as well as special rock-structures such as fluxion-phenomena, vesicles, effects of strain and fracture, *etc.* In short, the object of investigation should be not merely the composition of the rock, but its history.

Classification and nomenclature of rocks. Petrology has not yet arrived at any philosophical classification of rocks[1]. Further, it is easy to see that no classification can be framed which shall possess the definiteness and precision found in some other branches of science. The mathematically exact laws of chemistry and physics, which give individuality to mineral species, do not help us in dealing with complex mineral aggregates; and any such fundamental principle as that of descent, which underlies classification in the organic world, has yet to be found in petrology. Rocks of different types are often connected by insensible gradations, so that any artificial classification with sharp divisional lines cannot truly represent the facts of nature. At present, therefore, the best arrangement is that which brings together as far as possible, for convenience of description, rocks which have characters in common, the characters to be first kept in view being those which depend most directly upon important genetic conditions. The grouping adopted below must be regarded as one of convenience rather than of principle.

In a perfect system the nomenclature should correspond with the classification. This is, of course, impossible at present in petrology. Moreover great confusion has arisen in the nomenclature of rocks in consequence of the rapid growth of descriptive petrography. Many of the names still in use are older than the modern methods of investigation: they were given at a time when trivial distinctions were emphasized, while rocks essentially different were often classed together. Later writers, each in his own way, have arbitrarily extended, restricted, or changed the application of these older names, besides introducing new ones. The newer rock-names need cause no confusion, provided they are employed in a strict sense. Thus 'foyaite' should be used for rocks like that of Foya, specimens of which are in every geological museum: to extend the name to all nepheline-bearing syenites is to introduce needless ambiguity. In practice perhaps the most convenient usage is to speak of 'the Foya type,' 'the Ditro type,' *etc.*,

[1] For a historical sketch of the subject see Cross, *Journ. Geol.* (1902) x, 331–376, 451–499.

referring in each case to a described and well-known rock. There remain the names employed for families of rocks: some of these are old names, such as granite and syenite, which have come to have a tolerably well understood signification, not always that first attached to them; others, such as peridotite, have been introduced to cover rocks not recognized as distinct families by the earlier geologists. A division of a family is often designated by prefixing the name of some characteristic mineral of that division; *e.g.* hornblende-granite, hypersthene-andesite, *etc.*

These remarks apply more especially to igneous rocks, which we shall consider first. Such rocks, formed by the consolidation of molten 'magmas,' differ from one another in character, the differences depending partly on the composition of the magma in each case, partly on the conditions attending its consolidation. The composition is to some extent indicated by the essential minerals of the rock, which thus become an important, if not logically the prime, factor in any genetic classification. It is evident, however, that a mere enumeration of the minerals of a rock, without taking account of their relative abundance, cannot give a very precise idea of the bulk-analysis[1]; while, on the other hand, it appears on examination that magmas of very similar composition may, under different conditions of consolidation, give rise to widely different mineral-aggregates. Again, many rocks consist only in part of definite minerals, the residue being of unindividualised matter or 'glass.'

To diverse conditions of consolidation must be referred differences in coarseness or fineness of texture, the presence or absence of any glassy residue, the evidence of one or more than one distinct stage in the solidification, and, in general, the peculiarities in the mutual arrangement of the constituent minerals, which collectively are termed the 'structure' of the rock.

The massive igneous rocks will first be divided into three groups: abyssal or *plutonic*, *hypabyssal*, and superficial or

[1] This difficulty is only partially evaded by ranking some of the constituent minerals as *essential* and others as *accessory*.

volcanic. These names express the different geological relations of the several groups as typically developed, but the divisions themselves are based upon the characteristic structural features which different conditions of consolidation have impressed upon the rocks. Under each of these three heads the various rock-types will be grouped in families founded proximately on the mineralogical, ultimately on the chemical, composition, though this cannot be done without some few inconsistencies. The families will be arranged roughly in order from the more acid to the more basic, but it must be remembered that such an arrangement in linear series can represent only very imperfectly the manifold diversity met with among igneous rocks.

A. PLUTONIC ROCKS

The rock-types to be treated under the head of plutonic or abyssal are met with, in general, in large rock-masses which have evidently consolidated at considerable depths within the earth's crust. Transgressive as regards their actual upper boundary, their geological relations on a large scale are, as a rule, only imperfectly revealed by erosion; so that their actual form and extent are often matters of conjecture. Some of the masses seem to be of the nature of great laccolites; others have been supposed to mark reservoirs of molten magma, which once furnished the material of minor intrusions and surface volcanic ejectamenta. The immediate apophyses of the large masses have similar petrographical characters.

The distinctive features of these rocks of deep-seated consolidation are those which point to slow cooling (not necessarily slow consolidation) and great pressure. The rocks are without exception *holocrystalline*, *i.e.* they consist wholly of crystallized minerals, with no glass. The texture of plutonic rocks may be comparatively coarse, *i.e.* the individual crystals of the essential minerals may attain considerable dimensions. The typical structure is that known as *hypidiomorphic*, only a minor proportion of the crystals being 'idiomorphic' (*i.e.* developing their external forms freely), while the majority, owing to mutual interference, are more or less 'allotriomorphic' (taking their shape from their surroundings)[1].

Sequence of crystallization. The terms just introduced are used with a relative signification; so that a given mineral in a rock may be allotriomorphic towards certain associated minerals and idiomorphic towards others. By observing such points we are able to make out the order in

[1] This is the terminology used by Rosenbusch. Zirkel has adopted Rohrbach's terms *automorphic* and *xenomorphic* in the same senses. Pirsson has suggested the term *anhedron* (with adjective *anhedral*) for a crystal not possessing external crystal-faces: *Bull. Geol. Soc. Amer.* (1895) vii, 492.

which the several minerals composing an igneous rock have crystallized out from the parent rock-magma. It is found that there is in many plutonic rocks a 'normal order of consolidation' for the several constituents, which holds good with a high degree of generality. It is in the main, as pointed out by Rosenbusch, a law of 'decreasing basicity.' The order is briefly as follows.

I. Minor accessories (apatite, zircon, sphene, garnet, *etc.*) and iron-ores.

II. Ferro-magnesian minerals:—olivine, rhombic pyroxenes, augite, ægirine, hornblende, biotite, muscovite.

III. Felspathic minerals:—plagioclase felspars (in order from anorthite to albite), orthoclase (and anorthoclase).

IV. Quartz, and finally microcline.

In many rocks such minerals as are present follow the above order. The most important exceptions are the intergrowth of orthoclase and quartz and the crystallization of quartz in advance of orthoclase in some acid rocks, and the variable relations between groups II. and III. in the more basic rocks. The order laid down applies in general to parallel intergrowths of allied minerals: thus when augite is intergrown with ægirine or hornblende, the former mineral forms the kernel of the complex crystal and the latter the outer shell; when a plagioclase crystal consists of successive layers of different compositions, the layers become progressively more acid from the centre to the margin.

Certain constituents having variable relations are omitted from the foregoing list. Thus nepheline and sodalite belong to group III., but may crystallize out either before or after the felspars.

Varieties of structure in plutonic rocks. The typical structure of rocks of plutonic habit is that implied in the foregoing remarks, and is known as the *granitoid* or 'eugranitic' structure. Among the more special modifications frequently met with are those depending upon the simultaneous crystallization of two of the essential minerals, giving

rise to the so-called 'graphic' intergrowths, usually on a microscopic scale. The resulting *micrographic*, micropegmatitic or granophyric structure is most common in the quartz-bearing rocks, and arises there from an intimate interpenetration of part of the felspar with quartz (fig. 4, *C*). Within a certain area of a slice the quartz of such an intergrowth behaves optically as if it were a single crystal, the whole becoming dark between crossed nicols in one position. On rotation the felspar can be made to extinguish in its turn. Intergrowths of other minerals (*e.g.* augite and felspar) are less common. In both granitoid and micrographic rocks there sometimes occur vacant interstitial spaces or little cavities of irregular shape, into which project the sharp angles of well-formed crystals. Such rocks are said to have a *miarolitic* or *drusy* structure, but this peculiarity is often obscured by secondary products occupying the druses.

Opposed to the granitoid is the *granulitic* structure. In this a section of the rock appears as a mosaic of roughly equidimensional grains, usually of small size. There is in some cases a tendency to crystallographic development, or again the earlier-formed minerals tend to take on rounded outlines. The structure probably results from movement during the process of consolidation, and we shall see that very similar appearances may be produced by the deformation and crushing of already solidified granitoid rock-masses.

Both granitoid and granulitic rocks sometimes exhibit in greater or less degree a *parallel* disposition of elongated or tabular crystals of felspar, mica, *etc.*, indicative of some flowing movement of the rock-magma subsequent to the separation of those crystals. With this there may be a certain banding of the rock, due to alternations of slightly different types (mineralogically or structurally), which is known as a *gneissic* structure. These characters, however, may also have a quite different and secondary origin.

Traversing plutonic rock-masses of normal structural types, or bordering them as an irregular fringe, may often be found strikingly coarse-textured or *pegmatitic* modifications, with a

strong tendency to graphic intergrowths[1] (fig. 4, *C*). While clearly related to the associated plutonic rock-masses, these pegmatitic rocks differ from them mineralogically in the sense of being somewhat more acid, and they are further characterized by the frequent occurrence of special minerals, often including compounds of the rarer chemical elements. They are usually regarded as representing the final (pneumatolytic) phase of consolidation of the rock-magmas from which they were formed. The lighter-coloured veins and streaks often seen traversing plutonic rocks are in many respects comparable with the pegmatites. They often show a coarser texture and a more acid composition than the main mass in which they occur; and, though they more or less clearly cut the latter, the relations are such as to prove that their origin is bound up with that of the main rock-mass. They are sometimes spoken of as (relatively) *acid excretions* from the crystallizing magma.

Contrasted with these, there occur in many plutonic rocks darker and finer-textured ovoid or irregularly rounded patches which are usually considered as (relatively) *basic secretions* from the magma, belonging to an early stage in the process of consolidation. Composed in general of the same minerals as the enclosing rock, they are richer in the earlier-formed—which are also the denser and more basic—constituents (fig. 6, *B*). The lighter-coloured veins, on the other hand, are relatively rich in the later-formed and more acid minerals.

The typical plutonic rocks are *non-porphyritic*, *i.e.* there is evidence of but one continuous process of consolidation. In many hypabyssal and almost all volcanic rocks, some one, or more, constituent (usually a felspar) occurs in two distinct generations with different habits and characters, belonging to an earlier and a later stage of the consolidation. This is the 'porphyritic' structure, and is typically wanting among plutonic rocks, which have what has been termed an 'even-grained' character ('körnig' of Rosenbusch). In some of the plutonic rocks, however, and especially among the granites, occur

[1] The original pegmatite of Haüy was such an intergrowth of quartz and felspar ('graphic granite'), but the modern usage of the name is more extended.

relatively large crystals of felspar, which give a *porphyritic* character to the rock of which they form part, and perhaps point to different conditions from those under which the main mass of the rock consolidated; but even here there is no sharp division between an earlier and a later period of crystallization, such as is indicated in the volcanic rocks.

We shall consider the several families in an order which corresponds roughly with their chemical relationship, beginning with the acid rocks and ending with the ultrabasic.

CHAPTER II

GRANITES

The granites are even-grained holocrystalline rocks composed of one or more alkali-felspars, quartz, and some ferro-magnesian mineral, besides accessory constituents. The rocks are generally of medium to rather coarse grain, and the tendency of the crystals as a whole to interfere with one another's free development gives what Rosenbusch styled the hypidiomorphic structure.

According to their characteristic minerals, after felspars and quartz, the rocks are described as *muscovite-*, *biotite-*, *hornblende-*, and *augite-granites*; and this division corresponds often with different chemical composition, from more to less acid types. *Tourmaline-granite* must be considered a special modification of the above, and, in particular, of the more acid kinds. With the granites we shall also include certain rocks (*aplite*, *pegmatite*, *greisen*) associated with granites but differing from them in important structural and mineralogical characters. Some of them never form, like the true granites, large bodies of rock.

Constituent minerals. Felspars make up the greater part of a granite, a potash- and a soda-bearing felspar commonly occurring together. The potash-felspar is often *orthoclase*, either in simple crystals or in Carlsbad-twins, the Baveno-twin being uncommon. When fresh, it shows its cleavages and sometimes a slight zonary banding, but these appearances are lost when the mineral is altered to any extent. The common decomposition-processes give rise either to finely divided kaolin or to minute flakes of mica. When the latter are large enough to be clearly distinguished, they are often seen to lie along the cleavage-planes of the felspar. Decomposition often begins in the interior of a crystal, which may be clouded or completely obscured while the margin remains clear. Instead of orthoclase

we may find *microcline*, which is usually the last product of consolidation in the rock. It shows commonly a very characteristic 'cross-hatched' appearance between crossed nicols, due to complex lamellar twinning on a minute scale (fig. 4, *A*). The soda-felspars of granite range from *albite* to *oligoclase*. One or other variety accompanies the potash-felspar in varying relative proportions, and in the most typical 'soda-granites' albite is

FIG. 4. DRAWN WITH CROSSED NICOLS; ×20.

A. Microcline, showing 'cross-hatching,' from granite near Dublin.

B. Microperthitic intergrowth of microcline and albite, from granite, Rockport, Massachusetts.

C. Micrographic intergrowth of felspar and quartz, from pegmatite vein. Dalbeattie, Galloway: the felspar itself is a microperthite.

the predominant felspar. Parallel intergrowths of a potash- and a soda-felspar (*microperthite*) are very common (fig. 4, *B* and *C*).

The *quartz* of the granites does not usually show crystal boundaries, except on the walls of drusy cavities or when the mineral is enclosed by microcline. Its most characteristic inclusions are fluid-cavities. These are sometimes in the form

of 'negative crystals,' either dihexahedral pyramids or elongated prisms; more usually the shape is rounded or irregular. The fluid-pores often occur with a definite arrangement along certain planes, appearing in a section as lines. The enclosed liquid does not fill the cavity, but leaves a bubble, which is mobile. In some cases the liquid is brine, and contains minute cubes of rock-salt. In others liquid carbonic acid occurs instead of, or in addition to, water, and in some cases we see one bubble within another. Glass- and stone-cavities are less abundant. Sometimes extremely fine needles are enclosed: these seem to be rutile, and sometimes show the characteristic knee-shaped twin.

The dark micas of granites are usually termed *biotite*. This may be considered to include varieties rich in ferrous oxide (the haughtonite of many Scottish and Irish granites), or in ferric oxide (lepidomelane). The mineral builds roughly hexagonal plates, which, cut across, give an elongated section showing the strong basal cleavage. A lamellar twinning parallel to the base is probably common, but, owing to the nearly straight extinction, it is not often conspicuous. The fresh biotite is deep brown, with intense pleochroism. Its common inclusions are apatite, zircon, and magnetite, and the minute zircons are always surrounded by a 'halo' of extremely deep colour and intense pleochroism[1] (fig. 5, *A*). Decomposition often produces a green coloration and ultimately a green chloritic pseudomorph with secondary magnetite-dust. This magnetite may be reabsorbed, restoring the brown colour but with less pleochroism and with loss of cleavage.

The colourless, brilliantly-polarizing *muscovite* forms rather ragged flakes, posterior to the biotite or partly in parallel intergrowth with it (fig. 5, *A*). It is always clear, and is not susceptible to weathering. A lithia-mica, in large flakes, takes the place of muscovite in some greisens and pegmatites.

The crystals of *hornblende* are irregularly bounded, or at least without terminal planes. They show the prismatic cleavage and occasionally lamellar twinning parallel to the orthopinacoid.

[1] On the significance of these haloes, due to radio-activity, see Joly, *Phil. Mag.* (1907) xiii, 381–383, and *Radioactivity and Geology* (1909) 64–69; Mennell, *G. M.* 1910, 15–19, pl. v.

The colour is green or brownish green, with marked pleochroism, and the extinction-angle in longitudinal sections about 15°. The common decomposition-products are a green chloritic substance or an epidote and quartz.

When *augite* occurs, it is commonly the variety malacolite or diopside, colourless in slices, and may be more or less perfectly idiomorphic. When altered, it may be either uralitized or decomposed into a green chloritic mineral or into a mixture of serpentine and calcite. The augite is sometimes accompanied by a rhombic pyroxene (enstatite), and in one remarkable group of granitic rocks the dominant ferro-magnesian element is *hypersthene*.

Iron-ores are not plentiful in granites. *Magnetite* may occur or hæmatite, either opaque or deep red; *pyrites* is also found as an original mineral.

Acute-angled crystals of light brown pleochroic *sphene* (titanite) are often seen, and in the less acid granites are abundant. Rounded grains may occur instead. The high refractive index and other optical properties enable the mineral to be readily identified. The little prisms of *zircon* are even more highly refractive; but when they occur, as they often do, enclosed in the biotite, the pleochroic halo is liable to obscure their nature. *Apatite* builds narrow colourless prisms, and often penetrates the biotite. Small reddish *garnets* occur in some muscovite-granites and aplites. Rarer minerals are *cordierite*, usually pseudomorphed by the micaceous substance termed pinite, and *andalusite*, coated with flakes of muscovite. Where these are found, it is probable that the granite-magma has dissolved argillaceous matter from neighbouring sedimentary rocks. Another unusual mineral is *allanite* or *orthite*[1].

Tourmaline characterizes a common modification of granite, especially near the margin of a mass. It may be in good crystals, but more frequently has ragged outlines. The rude cross-fracture is often apparent (fig. 9, *A*). The colour is brown, sometimes with patches of blue, and the dichroism is strong, the strongest absorption being for vibrations transverse to the long axis (the 'ordinary' ray).

[1] Flett, *G. M.* 1898, 388–392.

Structure. In the granites the normal order of crystallization of the constituent minerals rules in most cases. The minor accessory minerals crystallized out first, and are thoroughly idiomorphic, *i.e.* have taken their shape without external interference. The ferro-magnesian minerals have in general preceded the felspars, being often embraced or even enclosed by them, though the felspars may tend also to take on partial crystal-outlines. Rarely does, *e.g.*, mica occur interstitially to felspar. Biotite moulded on muscovite is not so rare. Apart from micrographic structures, the felspars, except microcline, have crystallized prior to the quartz, exceptions being infrequent. Where micrographic intergrowths occur, the felspar may be either orthoclase or a plagioclase. We need not further specify other structural peculiarities such as the miarolitic, the porphyritic, and the spheroidal or orbicular.

Leading types. Almost all the true granites contain a brown mica. If a white mica be present in addition, we have *muscovite-granite* ('two-mica granite' or 'granite proper' of the Germans, 'granulite' of the French[1], 'binary granite' of some American writers[2]). Such rocks are commonly somewhat more acid in composition than those with dark mica only. The Carboniferous granites of Cornwall and Devon afford good examples. They consist of orthoclase, a plagioclase, quartz, and two micas, with the normal order of crystallization. The quartz has fluid-cavities, often enclosing minute cubes of rock-salt[3] (Dartmoor). Parallel intergrowths of biotite and muscovite are common. The minor constituents of the rock are magnetite, apatite, and zircon, the last, when it is enclosed in the biotite, being always encircled by the characteristic halo of intense pleochroism. More exceptional accessory minerals are andalusite, in pleochroic crystals coated by flakes of muscovite (Cheesewring), and 'pinite' pseudomorphs after cordierite (Land's End). Tourmaline is common, and the rocks

[1] The granulite of German and English petrologists has a different signification.

[2] This term, however, has also been applied to rocks consisting essentially of felspar and quartz, without mica.

[3] Hunt, *G. M.* 1894, 102–104.

graduate into tourmaline-granites, especially near the margin of an intrusion[1].

The post-Ordovician granites which occupy so large a tract in Leinster[2] (*e.g.* near Dublin) are of a different type (fig. 5, *A*). They also have two micas, often in parallel intergrowth, and apatite and zircon are characteristic accessories; but the

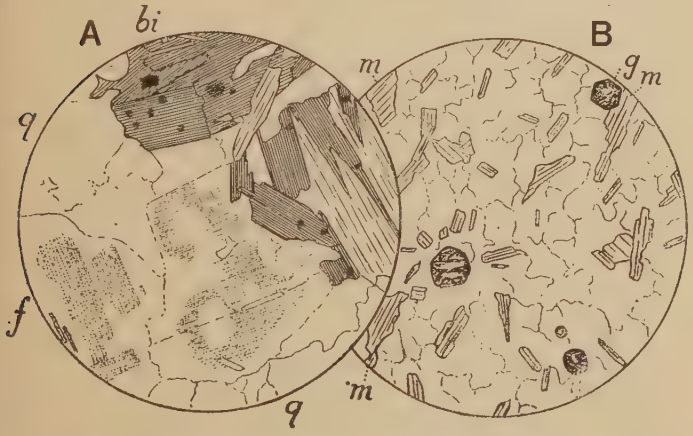

FIG. 5. GRANITIC ROCKS, KILLINEY, NEAR DUBLIN; ×20.

A. Muscovite-Biotite-Granite: composed of two micas (partly in parallel intergrowth), two felspars, and clear quartz (*q*). The biotite (*bi*) shows strongly pleochroic haloes round minute enclosed zircons. The plagioclase felspar (*f*) is often turbid in the interior, owing to alteration.

B. Aplite, veining the preceding rock: a finer-grained aggregate of quartz and felspars (plagioclase and microcline), with abundant flakes of muscovite (*m*) and scattered crystals of garnet (*g*).

potash-felspar is microcline, and is the latest product of crystallization. A plagioclase felspar is plentiful, and exceptionally albite is the only felspathic element present (Croghan Kinshelagh in Wexford). Little crystals of garnet occur in some

[1] See various *Memoirs* accompanying maps of the Geological Survey.
[2] Sollas, *Trans. Roy. Ir. Acad.* (1891) xxix, 427–512.

instances (Three Rock Mountain near Dublin). This mineral is found also in the granite of Foxdale in the Isle of Man, a closely similar rock, in which the dark mica is very subordinate to the white. Another well-known microcline-bearing rock is the 'grey Aberdeen granite' of Rubislaw, *etc.* Similar rocks are found in Donegal.

Rocks in which muscovite is only sparingly or occasionally present form a link with the next division. The Skiddaw granite is of this character[1]. Here the quartz is in great part of prior crystallization to the orthoclase, or there may be some micrographic intergrowth of the two minerals. Felspar-quartz-rocks free from mica are found among the pre-Cambrian intrusions of Ercal in the Wrekin district and of the Malverns. Here too the quartz has crystallized, or has finished crystallizing, before the dominant felspar, which is often microcline. These rocks seem to have affinities with the pegmatites.

The commonest division of the granite family is perhaps *biotite-granite* (Fr. granite, Ger. Granitit), characterized by containing a brown mica to the exclusion of muscovite, hornblende, or augite. Such a rock may consist, *e.g.*, of orthoclase, albite or oligoclase, quartz, biotite, and minor accessories, with the normal order of crystallization.

The relative proportions of the several minerals vary considerably. In the granites (Ordovician and some older) of Wales quartz is very abundant, and biotite (often chloritized) is only sparingly found. The dominant felspar is often a plagioclase, and some of these rocks would be placed among the 'soda-granites.' The St David's rock shows a strong tendency to the micrographic structure. In this and the allied granite of Hayscastle the dominant felspar is albite[2].

Biotite-granites of Palæozoic age are extensively developed in the Cairngorm and Monadhliath Mts and other parts of the Scottish Highlands. In many examples microcline partly or wholly takes the place of orthoclase (Malvern, Ross of Mull, Peterhead, *etc.*). Albite-veins intergrown in both orthoclase

[1] *Q. J. G. S.* (1895) li, 140. On the similar granite of Eskdale see Dwerryhouse, *ibid.* (1909) lxv, 61–63.

[2] Thomas and Jones, *Q. J. G. S.* (1912) lxviii, 387–388.

and microcline may sometimes be observed, *e.g.* in the Eskdale granite of Cumberland. In this rock the quartz is either intergrown in micrographic fashion with the orthoclase, or has crystallized before it. The latter is the case too in the well-known porphyritic granite of Shap in Westmorland[1] (fig. 6, *A*), which is further noteworthy for its abundant sphene.

FIG. 6. BIOTITE-GRANITE, SHAP FELL, WESTMORLAND; ×20.

A. The normal rock; showing apatite, sphene (*sp*), magnetite (*mg*), biotite (*bi*) partly chloritized, oligoclase (*og*), orthoclase (*or*), and quartz (*q*).

B. Dark basic secretion in the foregoing; of finer texture and richer in biotite, sphene, and apatite (*ap*).

Both micrographic and miarolitic structures characterize the Tertiary biotite-granites of the Mourne Mts, Carlingford[2], and Arran, the crystals on the walls of the druses presenting very perfect crystal boundaries. Microperthitic structure is very prevalent in the felspar of the Arran granites (fig. 7, *A*).

[1] Harker and Marr, *Q. J. G. S.* (1891) xlvii, 275–282.
[2] Sollas, *Trans. Roy. Ir. Acad.* (1894) xxx, 490.

Rocks belonging to this division cover large areas in South Africa. The coarse biotite-granite of the neighbourhood of Capetown is an example. The granite of the Matoppo Hills is rich in microcline. In Northern Rhodesia Mennell[1] has found primary epidote and allanite as frequent accessory constituents.

Less abundant than the types characterized by micas, and usually of less acid composition, is *hornblende-granite* (Ger.

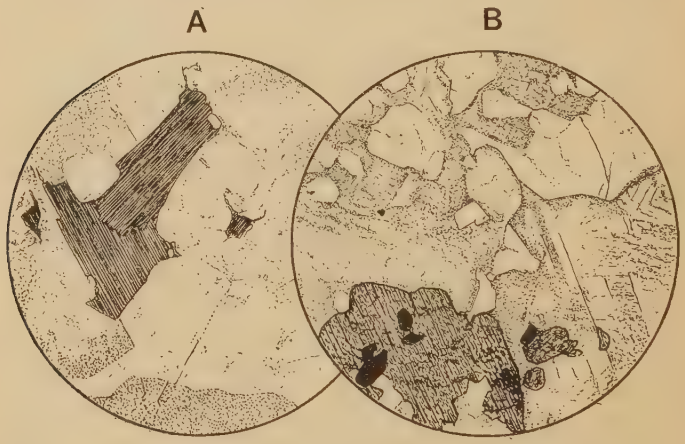

Fig. 7. Scottish Granites; ×20.

A. Biotite-Granite, Glen Rosa, Arran; showing biotite, felspar (largely microperthitic), and quartz.

B. Hornblende-Granite, Marsco, Skye; showing brownish green hornblende, opaque magnetite, oligoclase, orthoclase, and clear quartz.

Amphibolgranit), in which the distinctive mineral is a green hornblende, usually with biotite in addition. Some of the newer Palæozoic granites of Scotland are of this kind, such as that of Lairg and Ord Hill in Sutherland and the Criffel rock at Dalbeattie, in which, however, biotite often predominates. Here allanite is an occasional accessory. The Criffel granite graduates into a quartz-diorite. The hornblende-granite of

[1] *G. M.* 1902, 362, and 1903, 345–347.

Loch Etive is coarse-grained, and has porphyritic crystals of orthoclase. The rock quarried at Mount Sorrel near Charnwood, Leicestershire, is also in part a hornblende-granite, having that mineral associated with biotite. In Ireland a hornblende-granite has been described from Donegal, and others from the Newry district. These latter are of a relatively basic type, rich in oligoclase and the ferro-magnesian minerals, and are more accurately assigned to the quartz-monzonites.

Hornblende-granites are a common type among the Tertiary intrusions of Skye[1] (fig. 7, *B*), Rum, and Mull. In some the brownish green hornblende is associated with subordinate biotite. The rocks often show a rude micrographic structure and graduate into typical granophyres, in which the biotite, and to some extent the hornblende, give place to a greenish augite. A miarolitic structure is common, the cavities often obscured by secondary products.

If we exclude the granophyric varieties, *augite-granite* is by no means an abundant rock-type. An example, of Old Red Sandstone age, occurs in the Cheviots[2]. This consists of orthoclase, plagioclase, quartz, augite, exceptionally enstatite, biotite, iron-ores, and apatite, the quartz and orthoclase sometimes showing a micrographic intergrowth. The rock represents one of the most basic types of the granite family. In some of the granites, graduating into granophyres, of Mull and the Red Hills of Skye augite is the dominant coloured mineral, but it tends to be converted to hornblende, and primary hornblende often accompanies it. A typical augite-granite is found at Loch Ba, Mull (fig. 8, *A*).

Pyroxenic granites are widely distributed, though seldom in the same abundance as those types which carry hornblende and micas. In an augite-granite from Buluwayo, Rhodesia[3], the felspar is a microperthitic intergrowth of microcline and oligoclase. Another occurrence is at Mt Dromedary on the south coast of New South Wales[4].

[1] *Tertiary Igneous Rocks of Skye* (*Mem. Geol. Sur.* 1904) chap. x.

[2] Teall, *Brit. Petr.* pl. xxxix, fig. 2, and *G. M.* 1885, 112–116; Kynaston, *Tr. Edin. G. S.* (1899) vii, 390–397.

[3] Mennell, *The Geology of S. Rhodesia* (1904) 30–31.

[4] Anderson, *Rec. Geol. Sur. N. S. W.* (1892) ii, 148.

In Southern India a peculiar *hypersthene-granite* is of widespread occurrence, and has been described by Sir Thos. Holland[1] under the name charnockite. The typical rock consists of quartz and potash-felspar, with oligoclase, hypersthene, opaque iron-ore, and a little zircon, often with the addition of garnet. The dominant felspar seems to be microcline, often with parallel microperthitic intergrowths of plagioclase. The rock frequently shows some gneissic banding.

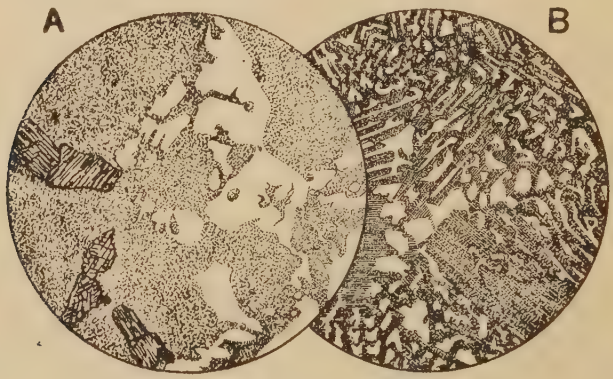

FIG. 8. MICROGRAPHIC INTERGROWTH OF FELSPAR (TURBID) AND QUARTZ (CLEAR); ×20.

A. Rude type of intergrowth in augite-granite. Loch Ba, Mull.

B. More delicate structure in granite (granophyre) of Beinn Dearg Mhòr, Skye.

Closely related to the granites is the rock known as *aplite* (granite-aplite). It occurs as veins in granite, but cutting the latter and traversing adjacent rocks, and by some petrologists it would be placed in the hypabyssal division. It is a fine-textured rock with 'panidiomorphic' to granulitic structure, and is somewhat more acid than the associated granite. A characteristic type occurs in connection with the muscovite-granites near Dublin (fig. 5, *B*). It consists of microcline,

[1] *Mem. Geol. Sur. Ind.* (1900) xxviii, 134–141.

with some oligoclase, quartz, muscovite, and red garnet. An aplite at Meldon in Devonshire[1] is of similar character, but instead of garnet contains topaz and some colourless or pale tourmaline. The Crosby dyke[2] in the Isle of Man may be referred here.

The *pegmatites* belonging to this family of rocks (granite-pegmatites) consist essentially of microcline or orthoclase and quartz, often with white mica and sometimes red garnet. The texture is often extremely coarse, and there is a frequent tendency to the graphic structure. Such rocks are extensively developed in connection with the Archæan gneiss of Sutherland. Others occur in Forfarshire[3]: these are often rich in muscovite, and locally carry garnet or tourmaline. It may be observed that these British pegmatites are not rich in rare or special minerals. In the United States, on the other hand, many of the most noted mineral-localities are furnished by pegmatites of this kind; *e.g.* Stoneham and Hebron in Maine, Chesterfield in Massachusetts, Haddam in Connecticut, Pike's Peak in Colorado, and Harney's Peak in the Black Hills of Dakota.

The *tourmaline-granites* appear as modifications of more normal granitic rocks. The tourmaline seems to take the place of the mica (fig. 9, *A*). As a further modification, the felspars may be replaced partly or wholly by tourmaline and quartz, the former sometimes occurring in little needles with radiate grouping embedded in clear quartz. The extreme modification is a tourmaline-quartz-rock or *schorl-rock* (fig. 9, *B*), in which felspar is wholly wanting, while tourmaline may occur in two or more habits, as crystals or grains and as groups of needles. All these types are illustrated among the Cornish and Dartmoor granites. A curious variety known as luxulyanite has been described by Dr Bonney[4] (fig. 10, *A*). Here the conversion of felspars into clear quartz, crowded with radiate groups of tourmaline needles, can be traced in various stages, the little

[1] Teall, *Brit. Petr.* p. 316; McMahon, *G. M.* 1901, 316–319.
[2] Hobson, *Q. J. G. S.* (1891) xlvii, 440.
[3] Barrow, *G. M.* 1892, 64; *Q. J. G. S.* (1893) xlix, 332–336.
[4] *Min. Mag.* (1877) i, 215–222; Semmons, *Pr. Liverp. G. S.* (1878) iii, 357–358.

needles, about ·03 inch in length, giving pale brown and light indigo colours for longitudinal and transverse vibrations respectively, while a brown tourmaline in distinct grains has been supposed to represent the mica of the granite. In general a blue colour seems to characterize especially tourmaline which replaces felspar (fig. 9, *C*). A schorl-rock from Trowlesworthy Tor contains fluor[1].

Fig. 9. Tourmalinization of Granites; ×20.

A. Conversion of biotite to brown tourmaline, Busava, Cornwall. The other constituents are much-decomposed felspar and clear quartz.

B. Final result of change, schorl-rock, Sheep Tor, Dartmoor. The rock consists wholly of tourmaline (brown with patches of blue) and clear quartz, largely of new formation.

C. Tourmaline-Granite, Ivybridge, Dartmoor. Tourmaline replacing a felspar crystal is deep blue, while the rest of the same crystal of tourmaline is brown.

The rock known as *greisen* (hyalomicte of French writers) consists essentially of quartz and white mica, which seems to be often a lithia-bearing variety. The Cornish greisens[2] are

[1] Worth and Bonney, *Trans. Roy. Geol. Soc. Cornw.* (1884) x, 177–188.

[2] Teall, *Brit. Petr.* 315 (St Michael's Mount); Scrivenor, *Q. J. G. S.* (1903) lix, 149–158 (Cligga Head).

apparently a modification of the granite in the same sense as the tourmaline-rocks are, but with a different result. The place of the felspar is taken by mica and topaz, though tourmaline is also met with. Closely connected with the greisens, and, like them, developed usually along joint-planes in the granite, are *tinstone-veins*. Here cassiterite is the characteristic mineral, associated with topaz, white mica, quartz, *etc.*, and

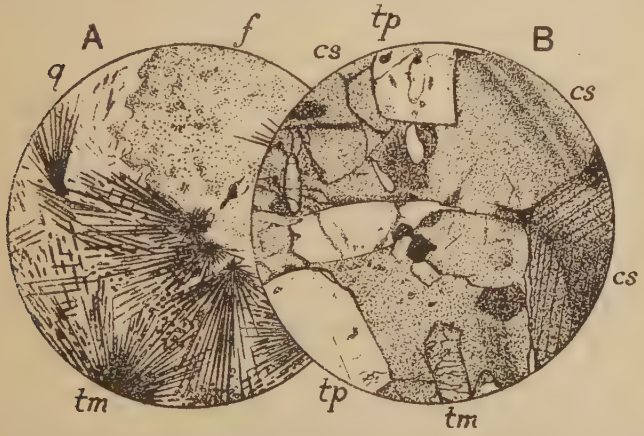

Fig. 10. Pneumatolytic modifications of Granite, Cornwall; ×20.

A. Schorl-rock (Luxulyanite), Luxulyan; showing replacement of felspar (*f*) by clear quartz (*q*) and radiating needles of blue tourmaline (*tm*).

B. Tinstone vein, Single Rose. The cassiterite (*cs*) varies in colour, partly in concentric zones: one crystal shows the prismatic cleavage and the twinning on the dome plane. The other constituents are clear topaz (*tp*) and small crystals of tourmaline (*tm*).

often a little brown tourmaline, derived from the biotite of the granite (fig. 10, *B*).

In conclusion we will note some examples of the dark, fine-grained, ovoid patches frequently enclosed in granitic rocks, and regarded as *basic secretions* separated out from the granite-magma at an early stage, not necessarily *in situ*. J. A. Phillips[1]

[1] *Q. J. G. S.* (1880) xxxvi, 1–21; (1882) xxxviii, 216–217.

described such patches from the muscovite-granites of Gready in Cornwall and Foggen Tor on Dartmoor and the biotite-granites of Shap and Peterhead, and he distinguished them from foreign fragments caught up and metamorphosed by the magma. The characteristic of the true secretions is that they consist of the same minerals as the enveloping rock, but contain the earliest products of crystallization—such as apatite, magnetite, and sphene—in larger proportions, and are also richer in the ferro-magnesian relatively to the felspathic elements of the rock. Sometimes, as in the Criffel granite, we may observe that hornblende is more plentiful as compared with biotite than in the normal rock, and similarly plagioclase felspar is more abundant relatively to orthoclase. The numerous dark patches in the Shap granite[1], rich in sphene and biotite (fig. 6, *B*), enclose, like the normal rock, large porphyritic crystals of orthoclase; but these are partially rounded and corroded, the margin of each crystal being replaced by plagioclase and quartz.

Gneisses. The term 'gneiss' is now used to denote, not a rock of some defined composition, but any crystalline rock possessing a *gneissic structure*. By this is to be understood a banded or streaky character due to the association or alternation of different lithological types in one rock-mass, or to the occurrence of bands or lenticles specially rich in some particular constituent of the rock. The structure is often found on a relatively coarse scale in rocks of granitoid texture, so that it is to be observed rather in the field or in large specimens than in microscopical preparations. It may, however, be associated with foliation on a smaller scale or with a partial parallel disposition of the elements of the rock. Gneisses, in this sense, may have the chemical and mineralogical composition of acid or intermediate or basic rocks, or may belong to types without parallel among the known products of igneous magmas.

It is generally recognized that gneisses as thus defined have originated in more than one way, although difference of opinion exists as to the interpretation of the facts in particular districts. There are (i) gneisses in which the banded arrangement, as

[1] *Q. J. G. S.* (1891) xlvii, 281–282, pl. xi, fig. 2.

well as the mineralogical constitution, of the rock-masses, is directly connected with an igneous origin; (ii) gneisses which represent the extreme phase of thermal metamorphism of sedimentary strata, the banding being the result of lithological differences between successive beds and seams in the original sediments; and (iii) gneisses which result from the bodily deformation of rock-masses, especially plutonic rocks, under the operation of powerful mechanical forces, the banding in this case standing in relation to the manner in which those forces have been applied. We are concerned in this place only with the first category: the other two will be dealt with in Chapters XXII and XXIII respectively.

In what may be distinguished as *primary igneous gneisses*, then, the banding is to be regarded as an original character of plutonic rocks, dating from the time when the rock in question was still fluid or partly fluid, and due to the different portions of a heterogeneous magma being drawn out in a flowing movement. Under this head, by general assent, are ranked the Lewisian gneisses of the North-West Highlands of Scotland. These rocks, apart from the innumerable dykes by which they are traversed, present much variation in character[1]. In the north, between Cape Wrath and Loch Laxford, hornblendic and micaceous gneisses predominate. From Scourie to beyond Lochinver and Loch Assynt the prevalent type is a pyroxenic gneiss, consisting essentially of augite or hypersthene (Kylesku), felspars, and quartz. There are also acid types, consisting mainly of felspars and quartz; while, on the other hand, the dominant rock encloses portions very rich in green hornblende. Hornblendic and micaceous gneisses predominate again about Gairloch and Loch Torridon, and a coarse hornblendic gneiss occurs in Lewis (Stornoway) besides other types. Many of these rocks show in varying degree the effects of dynamic metamorphism, but it is certain that much of the banding (as distinguished from foliation) may be ascribed to original conditions attending the intrusion of igneous magmas.

[1] Teall, *Ann. Rep. Geol. Sur.* for 1894, 280–281. For a fuller account see *The Geological Structure of the North-West Highlands* (*Mem. Geol. Sur.* 1907). The greater part of the area (in Lewis itself) is still unsurveyed.

In the South-Eastern Highlands (Forfarshire and Kincardineshire) Mr Barrow[1] has described certain micaceous gneisses which are clearly igneous intrusions, separable from the metamorphic gneisses with which they are associated. In one phase the rocks consist essentially of quartz, peculiar rounded crystals of oligoclase, muscovite, and biotite. Another phase shows abundant microcline, with a corresponding diminution of oligoclase, while at the same time the white mica predominates increasingly over the brown, and builds larger crystals. The author makes it clear that the remarkable features of these igneous gneisses are due in the main to crust-movements at the epoch of intrusion.

In the South Indian 'charnockites' (pyroxene-gneisses or pyroxene-granulites of some authors), already referred to under the head of hypersthene-granite, Holland has shown that the frequent banding and foliation are primary, but dynamic effects are also indicated, notably in the production of garnet. Lacroix[2] noted that in these rocks the felspars are often crowded with little round or elongated inclusions of quartz ('quartz de corrosion' of French writers) without the regularity of a graphic intergrowth. This is ascribed to secondary corrosion.

It is to be noted that the setting up of gneissic banding as a primary character in a plutonic rock implies two conditions, *viz.* a heterogeneous constitution of the mass and a differential movement of the nature of flowing. The heterogeneity may arise from imperfect differentiation or from imperfect admixture of two magmas or of an igneous magma with partially dissolved enclosed material. A good example, in which the requisite heterogeneity arose from an incomplete admixture of partially dissolved basic rock (eucrite) in a granite-magma, is afforded by the Tertiary gneisses of the Isle of Rum[3].

[1] *G. M.* 1892, 64–65; *Q. J. G. S.* (1893) xlix, 330–335.

[2] *Rec. Geol. Sur. Ind.* (1891) xxiv, 157–190.

[3] *Q. J. G. S.* (1903) lix, 207–213; *Tr. Edin. Geol. Soc.* (1905) viii, 346–348; *Geol. of Small Isles* (*Mem. Geol. Sur. Scot.* 1908) 105–114.

CHAPTER III

SYENITES AND MONZONITES

The syenites[1] are even-grained, holocrystalline rocks consisting essentially of alkali-felspars with ferro-magnesian constituents, typically in smaller proportion, and various minor accessories. The texture is often rather coarse to medium-grained, and the structure is that characteristic of plutonic rocks, the several minerals following the normal order of crystallization, and most of them having only imperfect crystal-outlines (hypidiomorphic structure of Rosenbusch). In many syenites, however, the order of crystallization is modified by simultaneous intergrowths of different minerals.

This family of rocks is less widely distributed and less abundant than the granites. Considered from a chemical point of view, it is characterized by a higher proportion of alkalies relatively to silica, and the richness in alkali-felspars is the mineralogical expression of this composition. In the more alkaline syenites the ferro-magnesian silicates also are of soda-bearing varieties.

The simplest type is a *hornblende-syenite*. When biotite more or less completely takes the place of hornblende, we have *mica-syenite*; and when augite occurs prominently, often in company with one or both of the other minerals named, *augite-syenite*. A subordinate content of free silica in rocks having the general characters of the syenite family gives rise to other types: *quartz-syenite*, *quartz-mica-syenite*, and *quartz-augite-syenite*. These may be regarded as connecting links with the granite family, in which quartz is a more abundant and essential constituent.

[1] The original syenite of Werner was the hornblende-granite of Syene or Assouan on the Nile. The name, however, has come to be universally applied to the family under notice, rocks often hornblendic but typically free from quartz.

On the other hand the coming in of a lime-soda-felspar as a prominent constituent in addition to the alkali-felspar gives rise to types intermediate between true syenites and diorites, and for these the name *monzonite* is employed. It was originally given to a particular type from the Monzoni district, in the Tirol, but has been employed by Brögger in a wider sense. This geologist has constituted a separate family to include those plutonic rocks in which orthoclase and a plagioclase felspar are represented in approximately equal proportions. It embraces quartz-monzonites at the one end and thoroughly basic types at the other.

Constituent minerals. In mode of occurrence, inclusions, alteration-products, *etc.*, the felspars of syenites resemble those of granites. Besides *orthoclase*, *microcline*, and *albite* or *oligoclase*, there occur felspars rich in both potash and soda, known as soda-orthoclase, soda-microcline, anorthoclase, *etc.* These are regarded by some mineralogists as intergrowths on an ultra-microscopic scale of a potash- and a soda-felspar (*cryptoperthite*). An evident parallel intergrowth of albite and microcline or albite and orthoclase (*microperthite*) is also frequent in the same rocks.

The common *hornblende* of syenites is partly idiomorphic but without terminal planes. It is of the green pleochroic variety, giving in vertical sections a maximum extinction-angle of 12° to 16°. Its inclusions and alteration-products are the same as in granite. The more alkaline syenites often contain instead a soda-bearing variety, either *barkevicite*, with intense brown absorption and pleochroism and an extinction-angle of about 12°, or bluish *arfvedsonite*. The pleochroism of the latter varies, but usually gives tones of greenish blue, grey-blue, and yellowish green.

The *augite*, when it occurs as an accessory, is colourless or very pale green, with the same properties as in granite. In the augite-syenites it has often a light brown to purplish brown colour, with distinct pleochroism, and this property seems to go with a certain content of titanium. Various types of schiller- and diallage-structures are sometimes seen, and may affect

only a portion—usually the interior—of a crystal (fig. 13, *B*). In the more alkaline syenites the pyroxene is often a bright green pleochroic *ægirine*, or again a paler green and less strongly pleochroic variety, intermediate between ægirine and common augite.

The *biotite* of the syenites is deep brown, becoming green only by secondary changes. In some alkaline syenites vibrations parallel to the cleavage-traces are almost completely absorbed. The mineral is roughly idiomorphic, except when intergrown with hornblende or augite.

When *quartz* occurs, it has the same characters as in granite, but is never very abundant. Most syenites contain plenty of *sphene* in good crystals showing the cleavages and often the characteristic twinning. *Zircon* is common in small prisms with pyramidal terminations, as in the granites. In some of the augite-syenites, however, it builds large crystals of simple pyramidal form. It is easily identified by its limpid appearance and extremely high refringence and birefringence. *Apatite* in colourless needles is widely distributed in syenites. The iron-ores are variable in quantity: they include *magnetite*, *ilmenite*, and *hæmatite*, the last two often in thin flakes enclosed in the felspars. Certain alkali-syenites contain the deep brown garnet, *melanite*.

Structure. The texture of the syenites and the mutual relations of their constituent minerals are normally similar to those observed in the granites, Rosenbusch's 'order of consolidation' being, as a rule, followed. In the typical hornblende-syenites there are few peculiarities. When quartz enters, it may be intergrown in micrographic fashion with part of the orthoclase, and this is specially the case in some augite-syenites. When plagioclase felspar is abundant, it is sometimes embraced by shapeless plates of orthoclase, and in the same rocks reversals of order between the bisilicates and the felspars may often be noticed.

Some syenites contain basic secretions, acid veins, pegmatite fringes and other peculiarities noticed under the granites. Parallel and gneissic structures sometimes come in locally.

Leading types. Syenitic rocks are but little developed in the British Isles. The name 'syenite' as found in many of the earlier writings and maps in this country is to be understood in the old sense of hornblende-granite (including also granophyre, *etc.*) and the identification of hornblende is in many cases erroneous. True syenites sometimes occur as local facies of granitic and dioritic rocks, and the plutonic complex of

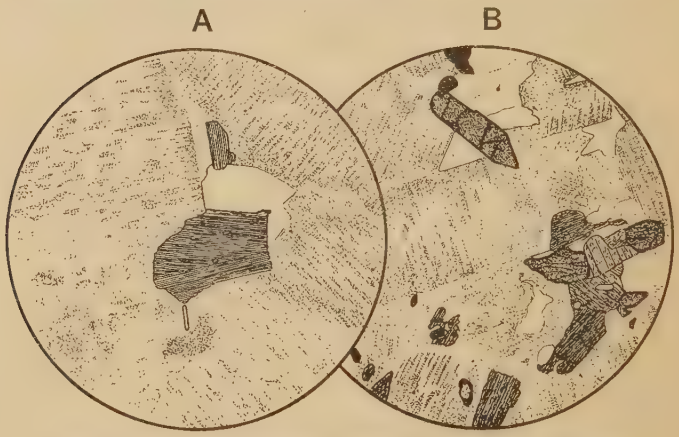

FIG. 11. QUARTZ-SYENITES (NORDMARKITES), NORDMARKEN, NORWAY; ×20.

A. Grorud: principally of microperthitic felspar, with biotite and interstitial quartz.

B. Near Christiania: here arfvedsonite is the coloured silicate, and sphene is conspicuous (a good crystal in upper part of figure).

Assynt, in the west of Sutherland, consists of alkaline syenites associated with nepheline-syenites. For any greater diversity of types we must go abroad.

Some *quartz-syenites* are merely local varieties of granites, into which they graduate, but others occur as independent masses. One type, of alkaline nature, is developed in force in the Christiania district, and is known as nordmarkite. Besides the dominant alkali-felspars and some interstitial quartz, it

contains, in different varieties, biotite or arfvedsonite or ægirine (fig. 11). The quartz-syenite of Cnoc na Sroine, Assynt[1], bears some resemblance to nordmarkite, but is almost devoid of any ferro-magnesian silicate. In one variety quartz occurs in conspicuous grains.

The rock taken as the type of *hornblende-syenite* is that of Plauen'scher Grund near Dresden (fig. 12, *A*). It is composed

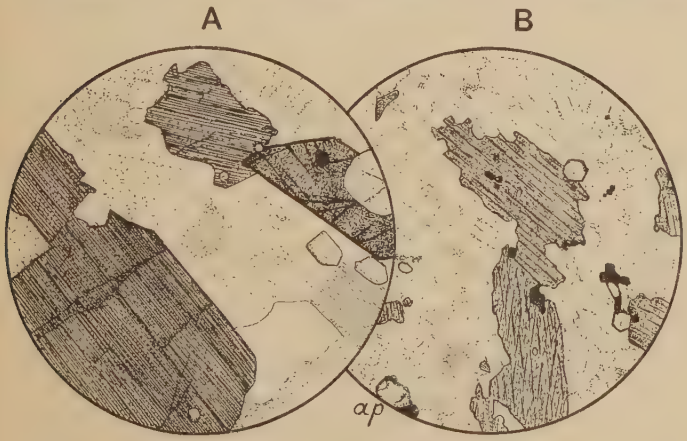

FIG. 12. HORNBLENDE-SYENITES; ×20.

A. Plauen'scher Grund, Dresden. The felspar, though not visibly perthitic, is a potash-soda-felspar. The other minerals are green hornblende, large crystals of brown sphene with apatite (to right), and a little interstitial quartz.

B. Ratagan Pass, Glenelg. The felspars are orthoclase and oligoclase, partly in microperthitic intergrowth.

essentially of soda-orthoclase[2], with only subordinate oligoclase, and green hornblende. Apatite, magnetite, and sphene occur as accessories, and in places a little quartz. There is a variety in which biotite occurs in addition to the hornblende. The rock encloses dark basic secretions richer in plagioclase,

[1] Teall, *G. M.* 1900, 385–392; Shand, *Tr. Edin. G. S.* (1910) ix, 382.
[2] Washington, *A. J. S.* (4) (1906) xxii, 129–135.

hornblende, apatite, magnetite, and sphene. Among scanty British representatives may be mentioned one from the Ratagan complex, Glenelg, Invernessshire (fig. 12, *B*). Here are darker and lighter varieties, including one almost purely felspathic[1].

The *mica-syenite* type, in which biotite predominates over hornblende, is of uncommon occurrence, except as a local variety of hornblende-syenite. Rosenbusch notes examples from Canada; one from Star Hill Mine, Portland West, P.Q., rich in apatite; another from Blessington Mine, Inchinbrooke, Ont., with some augite as well as mica. These rocks are free from quartz or plagioclase. Some mica-syenites in Hastings County, Ont., contain calcite as a primary constituent, presumably due to some incorporation of the neighbouring limestones. In Britain no typical mica-syenite has been recorded, but a rock from Three Tops Mt, Donegal, consists of orthoclase, biotite, and augite, with infrequent plagioclase[2].

In the *augite-syenites* in general the pyroxene is associated with more or less biotite or hornblende. A well-known rock of this kind (Larvik type) comes from Southern Norway (fig. 13, *B*). While augite is usually the dominant ferro-magnesian element, it is often accompanied by biotite, ægirine, hornblende, *etc.* Alkali-felspars (orthoclase, microcline, albite, cryptoperthite, *etc.*) make up the bulk of the rock, and are often intergrown with one another. Not infrequently they have a schiller-structure. A little quartz is rarely present; on the other hand nepheline and sometimes olivine may occur as minor accessories. The augite is occasionally green, but commonly light brown with a violet tone and slight pleochroism: schiller-structure is common. The hornblende is green or occasionally brown, the biotite a very deep brown. The latter mineral is roughly idiomorphic, except when it is massed round magnetite or forms a marginal intergrowth with augite. The iron-ores are magnetite and sometimes hæmatite: apatite is universal, but sphene is typically absent. Zircon is a constant accessory, and sometimes builds large crystals, giving the variety 'zircon-syenite' of von Buch and other early writers.

[1] *Geology of Glenelg* (*Mem. Geol. Sur. Scot.* 1910) 85.
[2] Hyland, *N.W. and C. Donegal* (*Mem. Geol. Sur. Ire.* 1891) 138–139.

These Norwegian 'larvikites,' together with the associated nordmarkites and other types, are common as erratics on the eastern coasts of England.

Rocks resembling the Larvik type occur near Sivamalai in the Coimbatore district of Madras[1], and again in the Transvaal (Hatherley, near Pretoria)[2]. A biotite-augite-syenite has been described also from Leeuwfontein, in the same district[3]. A

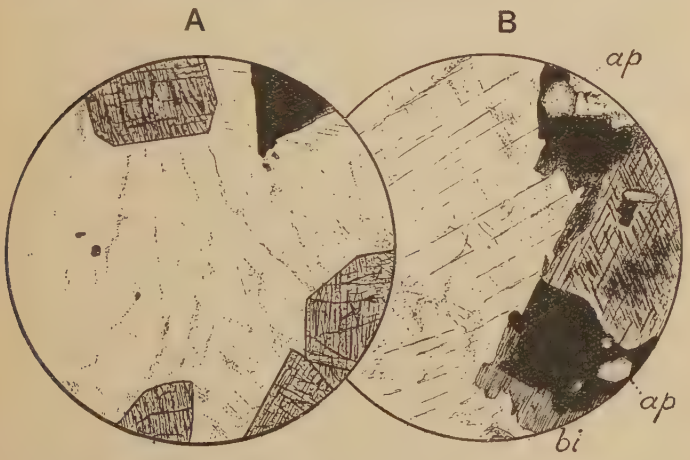

FIG. 13. AUGITE-SYENITES; ×20.

A. Marblehead, Massachusetts. Mostly of alkali-felspars, micro- to cryptoperthitic, with idiomorphic pale augite and opaque magnetite.

B. Larvik, Southern Norway. Pale brown augite with strong schiller-structure and fringed with brown hornblende and biotite (*bi*); some magnetite and apatite (*ap*); cryptoperthite felspar in large crystals.

rock from Buluwayo[4] is composed of microcline, augite, and hornblende. Numerous other types of augite-syenites have been described from Norway, Canada, Massachusetts (fig. 13, *A*),

[1] Holland, *Mem. Geol. Sur. India* (1891) xxx, 199–201.

[2] Henderson, *Transvaal Norites, Gabbros, and Pyroxenites* (1898) 46–48.

[3] Hall, *Rep. Geol. Sur. Transv.* for 1903, 38.

[4] Mennell, *G. M.* 1902, 365.

and other areas of alkaline plutonic rocks. At Carlingford, Co. Louth, is an isolated occurrence of a syenite with green augite and remarkably rich in sphene and apatite.

A special type of alkali-syenite is that in which brown garnet takes the place of the usual amphibole and pyroxene minerals. A *melanite-syenite* of this kind makes part of the Assynt complex at Cnoc na Sroine.

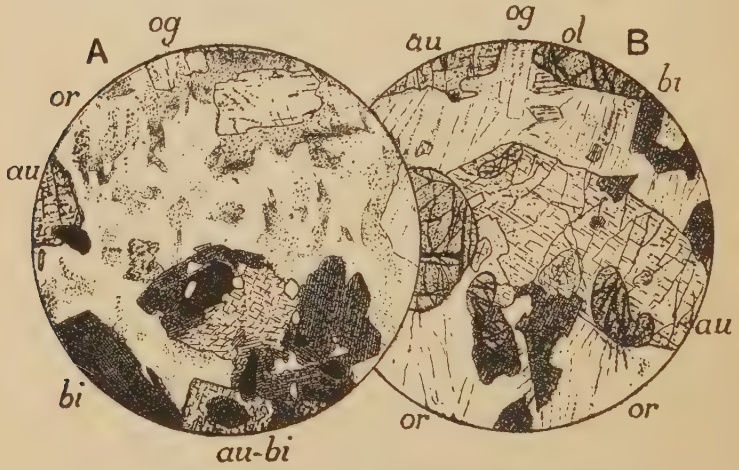

FIG. 14. MONZONITES; ×20.

A. Typical Monzonite, Predazzo, Tirol: showing apatite, magnetite, colourless augite (*au*) and brown biotite (*bi*) sometimes intergrown, oligoclase (*og*), and orthoclase (*or*).

B. Olivine-Monzonite (Kentallen type), Kentallen, near Ballachulish, Argyllshire. Here the ferro-magnesian minerals are in greater amount, and include abundant olivine (*ol*).

The typical *monzonite* of the Tirol is also an augite-bearing rock, and, as already remarked, contains in general a noteworthy amount of plagioclase felspar. This is enclosed, with other minerals, by relatively large crystals of orthoclase (fig. 14, *A*). Biotite is usually present, in flakes sometimes earlier, sometimes later, than the plagioclase. Sphene is

frequent, and zircon is often enclosed by the mica. Other constituents are apatite, magnetite, and pyrites, and in some varieties a little interstitial quartz. The name has, however, been extended to cover a series of types ranging from one relatively acid, with a notable amount of quartz, to others of basic composition, with olivine, and to a type consisting mainly of augite and magnetite with little felspar.

An extreme basic type, associated with other monzonites in the Highwood Mts, Montana, was described by Weed and Pirsson[1] under the name *shonkinite*. It consists of predominant augite with orthoclase, albite, and anorthoclase, apatite, biotite, olivine, *etc.*, and may be compared with the basic modifications of the rocks of Monzoni ('pyroxenites' of Brögger).

The 'newer granites' of Scotland, in Argyllshire and in Galloway, sometimes pass into quartz-monzonites and monzonites without quartz. At certain places in Argyllshire, and typically at Kentallen, near Ballachulish, occurs a remarkable basic rock comparable with the olivine-monzonites of Brögger (Kentallen type)[2]. It consists of olivine, pale green augite, plagioclase, and interstitial biotite and orthoclase. It shows considerable variation, sometimes approximating to the Shonkin type (fig. 14, *B*).

Here too may be mentioned the plutonic intrusive rocks of Charnwood in Leicestershire. They have often been termed syenites, but, excepting the granite of Mount Sorrel (p. 37), they seem to vary between quartz-syenites and quartz-diorites, with a strong tendency to the micrographic structure of the rocks known as granophyres. They are essentially augitic rocks, but the augite tends to pass into uralitic hornblende, and epidote is a characteristic secondary product in the rocks. Examples are seen at Groby, Bradgate Park, Markfield, and Garendon, all in the Charnwood Forest district[3].

[1] *Bull. Geol. Soc. Amer.* (1895) vi, 408–415; *cf.* 20*th Ann. Rep. U. S. G. S.* (1900) part III, 479–484, pl. LXXII.

[2] Teall, *Brit Petr.* pl. XVI, fig. 1, and *Ann. Rep. Geol. Sur.* for 1896, 22–23; Hill and Kynaston, *Q. J. G. S.* (1900) lvi, 531–540, pl. XXIX, XXX; Hill, *Summary of Progress Geol. Sur.* for 1899, 48–53.

[3] Bonney, *Q. J. G. S.* (1878) xxxiv, 214–218.

CHAPTER IV

NEPHELINE-SYENITES AND ALLIED ROCKS

The rocks here included are characterized chemically by their notable richness in alkali, and especially in soda. In their mineralogical constitution this appears not only in the presence of alkali-felspars to the exclusion of lime-bearing varieties, and in the very general occurrence of soda-bearing pyroxenes and amphiboles[1] (as in the alkali-syenites), but further in the presence as essential constituents of minerals of the *felspathoid* group. Under this head we include the sodic minerals nepheline, sodalite (with nosean), and primary analcime and the potassic mineral leucite. In other respects the nepheline-syenites and their allies have much in common with the alkali-syenites, with which they are very frequently associated in the field.

The various members of this family are medium to coarse-grained plutonic rocks composed essentially of alkali-felspars, one or more minerals of the felspathoid group, and various ferro-magnesian silicates. According to the dominant felspathoid mineral, we may distinguish *nepheline-syenites*, *sodalite-syenites*, and *leucite-syenites*, of which the first are the most important.

We shall also include here for convenience two rarer and more exceptional groups of rocks, which call for only brief notice. They are the *theralites*, characterized by the association of nepheline with a lime-soda-felspar (labradorite), usually with orthoclase in addition, and the *ijolites*, in which nepheline wholly takes the place of felspars.

Constituent minerals. The alkali-felspars in these rocks include *orthoclase*, *microcline*, and *albite*, separately or in association and very frequently in perthitic intergrowth.

The *nepheline* is of the variety known as 'elæolite,' in larger and less perfect crystals than the nepheline of volcanic rocks. If idiomorphic, it forms hexagonal prisms (fig. 15, *A*) with the

[1] Some types also are rich in the potash-silicate mica.

basal plane sometimes bevelled by narrow pyramid-faces. In more shapeless crystals the straight extinction can be verified by reference to rows of inclusions which follow the direction of the vertical axis, and seem to determine the alteration of the mineral. The crystals are colourless or often rather turbid, and give rise by decomposition to various soda-zeolites or to brightly polarizing prisms, fibres, and aggregates of cancrinite. A frequent associate of nepheline is *sodalite*, in dodecahedra or in allotriomorphic crystal-plates and wedges. It is colourless or faint blue in slices, and is easily recognized by its isotropic behaviour. It encloses fluid-pores, microlites of ægirine, *etc.*, and secondary products similar to those of nepheline. *Analcime* is another isotropic mineral of very low refractive index, and sometimes shows cracks corresponding with the cubic cleavage. It is found both as a primary mineral and as an alteration-product of nepheline and sodalite. This last remark applies also to *cancrinite*, a hexagonal mineral with prismatic cleavage, but seldom showing crystal-shape. With a very low refractive index it has a high birefringence, and gives brilliant polarization-tints.

Leucite is not actually found in any of these rocks, but in one rare type is represented by pseudomorphs preserving the characteristic crystal-form. These so-called 'pseudoleucites' are aggregates of such minerals as orthoclase, nepheline, and analcime.

The *biotite* of the nepheline-syenites is usually a variety with deep brown colour and intense pleochroism (lepidomelane). The common pyroxenes are pale green *ægirine-augite* and bright green pleochroic *ægirine*, the latter sometimes forming a border to the former. In the more basic rocks the purplish brown *titaniferous augite* is more usual. The most common amphibole minerals are deep brown *barkevicite*, greenish blue *arfvedsonite*, and a very deep bluish green variety named *hastingsite*. All these pyroxenes and amphiboles are soda-bearing minerals

Deep brown *melanite*, often with zonary colouring, is a constituent of certain rock-types. The commoner accessory minerals are *sphene*, *iron-ores*, and *apatite*. In the ijolites occurs *perovskite* in small octahedral crystals with greyish brown colour

and extremely high refractive index. *Calcite*, dissolved from contiguous limestones, is a constituent of some nepheline-syenites[1].

Structure. Most of the rocks in this family have something of the 'eugranitic' structure so general in plutonic rocks. Others have a different character determined by a general parallelism of tabular felspar crystals, a structure rather laxly termed 'trachytic[2].' As a rule the ferro-magnesian minerals have crystallized before the felspars and the felspathoid minerals later, but to this there are many exceptions. Moreover, intergrowths are very common both among the coloured and among the light minerals, and sometimes even between the former and the latter. Some nepheline-syenites again have a porphyritic structure from the development of large crystals of felspar.

Parallel and gneissic structures sometimes come in locally, and pegmatoid and aplitic modifications are found. Some nepheline-syenite-pegmatites, such as those of the Langesundsfjord in Southern Norway, are rich in numerous rare minerals, especially compounds of the 'rare earths.'

Leading types. The only British nepheline-syenites are those of the Assynt district in western Sutherland and Ross, and we are therefore largely dependent on foreign occurrences for illustrative examples.

A well-known *nepheline-syenite* is that of Serra de Monchique in Portugal[3] (Foya type). Here the felspar is orthoclase, and is in excess of the nepheline; sodalite is often present; the coloured minerals are subordinate hornblende, augite edged with ægirine-augite, and biotite; while apatite, magnetite, and abundant sphene are also present.

The nepheline-syenites of Assynt[4] are also of orthoclase-

[1] R. Workman, *G. M.* 1911, 193–200, pl. XII; Adams and Barlow, *Geology of the Haliburton and Bancroft Areas* (1910) 251, pl. LI.

[2] Brögger applies the name 'foyaite' to rocks with this structure and 'ditroite' to the granitoid nepheline-syenites, but these terms have by priority different significations.

[3] Sheibner, *Q. J. G. S.* (1879) XXXV, 42–47, pl. II.

[4] Shand, *Tr. Edin. G. S.* (1909–10) ix, 202–215, 376–416.

bearing types, but they show a special feature in the almost constant presence of melanite, and may be styled *melanite-nepheline-syenites*. The nepheline is sometimes idiomorphic (fig. 15, *A*), more often of interstitial occurrence, and again very frequently intergrown in the orthoclase, forming a network of slender curving threads (fig. 15, *B*). It is almost always decomposed, the chief alteration-product being very finely

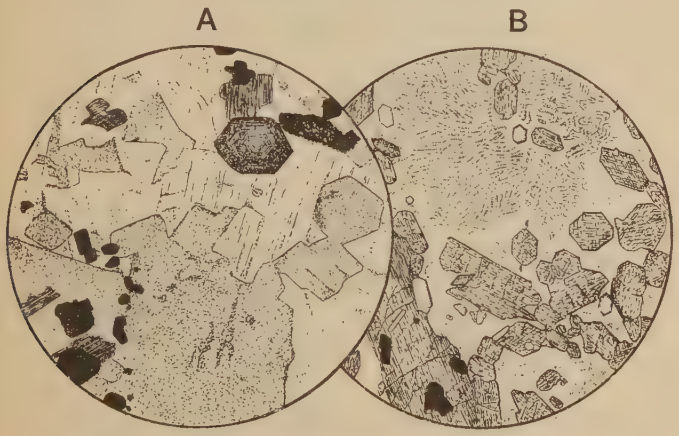

FIG. 15. NEPHELINE-SYENITES, ASSYNT, SUTHERLAND; ×20.

A. Loyne: showing idiomorphic nepheline (altered), orthoclase, biotite, deep brown melanite, and magnetite.

B. Elphin Bridge (Ledmore type): showing thread-like intergrowth of nepheline (now altered) in orthoclase; also idiomorphic green ægirine-augite with a deeper-coloured border.

divided white mica. The brown melanite is in crystals or irregular grains, with varying depth of colour. It is often accompanied by biotite, which has a greenish colour, probably due to alteration. There occurs also a soda-pyroxene showing different tones of green and sometimes a zonary structure. Sphene is very common, but appears to have arisen at the expense of the melanite. This change, as well as the destruction of the nepheline, may be attributed to dynamic metamorphism,

and has come about especially where the rocks have been crushed in the Moine overthrust.

One type, from the northern base of Cnoc na Sroine, consists of orthoclase and nepheline in about equal parts, with

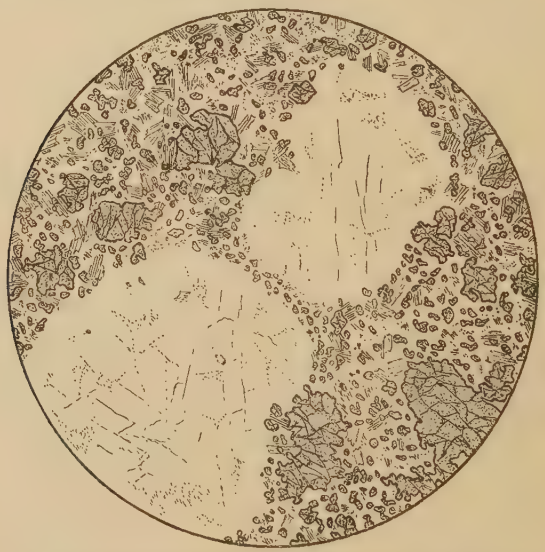

Fig. 16. Melanite-Nepheline-Syenite (Borolan type), Loch Borolan, Sutherland; ×5.

Showing orthoclase, melanite, and pale green biotite. The altered nepheline, with interstitial occurrence and partly intergrown in the orthoclase, does not appear. The clear spots, which have been likened to pseudoleucites, seem to be merely porphyritic crystals of orthoclase.

only a little melanite and greenish biotite[1]. In others the coloured minerals are more abundant, the pyroxene and melanite varying inversely. The Ledmore type of Shand is pyroxenic

[1] Teall, *G. M.* 1900, 387–388.

(fig. 15, *B*), while the Borolan type[1] is garnetiferous, with some green mica but usually no pyroxene (fig. 16). The latter rock has a porphyritic variety with conspicuous spots of orthoclase, rounded and shattered, and these were once believed to represent leucite crystals.

FIG. 17. NEPHELINE-SYENITES, LAAGENDAL, SOUTHERN NORWAY; ×20.

A. Kvelle: showing apatite and magnetite as accessories, brown biotite (*bi*) and green ægirine-augite (*au*) in parallel intergrowth, micro- and cryptoperthite felspar (*f*), and clear interstitial nepheline (*n*).

B. Lunde, near Larvik (Lardal type): showing abundant apatite and magnetite, pale augite and brown biotite, idiomorphic nepheline, and cryptoperthite felspar.

Much more wide-spread are those rocks in which potash- and soda-felspars occur together, with a diversity of microperthitic and cryptoperthitic intergrowths. Here belongs, *e.g.*, the nepheline-syenite of Montreal, composed of felspar, nepheline, various deep-coloured hornblendes, and biotite, with sodalite, melanite, sphene, *etc.* Other well-known examples are found in Southern Norway (fig. 17). One variety (Lardal type)

[1] Horne and Teall, *Tr. Roy. Soc. Edin.* (1892) xxxvii, 163–177, with plate; Teall, *G. M.* 1900, 389; Shand, *loc. cit.*

is usually of very coarse texture: a finer kind is represented in fig. 17, *B*. The abundant nepheline is in idiomorphic crystals. There is a considerable variety of alkali-felspars, cryptoperthite predominating. The ferro-magnesian minerals include deep brown mica and either a greenish ægirine-augite or the violet-brown augite noted in the Larvik syenite. Apatite is abundant, and olivine is an occasional constituent.

Nepheline-syenites in which albite (or sometimes oligoclase) is the sole or greatly predominant felspathic element are widely distributed in some parts of Ontario[1] The ferro-magnesian mineral is sometimes biotite, sometimes the deep blue-green amphibole hastingsite, and primary calcite is not uncommon. The proportion of nepheline varies, and is sometimes very high (Monmouth type). In the extreme case, where felspar is almost wanting, these rocks approach a type ('urtite' of Ramsay) known from Finland. At other localities are types very rich in dark minerals: these are comparable with the 'lujaurite' of Ramsay, but instead of ægirine have hastingsite and sometimes red garnet.

Sodalite not infrequently accompanies nepheline in rocks of this family, and is conspicuous, associated with various felspars, in the Ditro type, from Transylvania. Only exceptionally does this mineral so far take the place of nepheline as to constitute a distinct type of *sodalite-syenite*. Rocks of this kind occur in the Highwood Mts of Montana[2] and at Cottonwood Creek[3] in the same State. A sodalite-syenite occurs, with nepheline-syenite, at Belœil in the Montreal district. A very beautiful rock composed of sodalite and microperthite felspar forms veins in a nepheline-syenite in Ice River Valley, British Columbia[4]. It constitutes the most felspathic term in a series, the other extreme type being an ijolite[5]. Near Bancroft, in Ontario, also are rocks extremely rich in sodalite, associated

[1] Adams and Barlow, *Geology of the Haliburton and Bancroft Areas* (*Geol. Sur. Can.*) 1910.

[2] Lindgren, *A. J. S.* (1893) xlv, 290–297; Weed and Pirsson, *Bull. Geol. Soc. Amer.* (1895) vi, 416–417.

[3] Merrill, *Pr. U. S. Nat. Mus.* (1894) xvii, 671–673.

[4] Bonney, *G. M.* 1902, 199–206.

[5] Barlow, *Ottawa Natst.* 1902, 70–76.

with albite, nepheline, and biotite. In such cases it is probable that the sodalite has a pneumatolytic origin.

An *analcime-syenite* is found near Mauchline, Ayrshire[1]. It shows well shaped tabular crystals of felspar with a general parallel arrangement and in the interspaces the dark minerals embedded in abundant clear analcime. The felspars are anorthoclase bordered with orthoclase and occasional crystals of labradorite. The ferro-magnesian minerals are purplish titaniferous augite, ægirine, barkevicite, and arfvedsonite. Other constituents are ilmenite and apatite.

The best known example of *leucite-syenite* occurs at Magnet Cove, Arkansas[2]. The abundant pseudomorphs after leucite have the icositetrahedral form, and range up to 2 inches in diameter. They consist of a mixture of orthoclase and nepheline. The rest of the rock is made up of idiomorphic nepheline (with only a small amount of orthoclase), melanite, diopside, ægirine, and biotite.

The *theralites*, as has been said, differ from the nepheline-syenites in having a plagioclase felspar, though usually with orthoclase in addition. The original type is from the Crazy Mts, in Montana[3] (fig. 18, *B*). Here the idiomorphic augite, pale green to almost colourless in slices, is often surrounded by a narrow border of deep green ægirine. The felspar is partly a striated plagioclase, partly orthoclase or anorthoclase. A sodalite mineral occurs in addition to the nepheline, and the other constituents are biotite, apatite, and a little iron-ore. Theralites, of melanocratic type, have been described from Barshaw near Paisley and from Lugar in Ayrshire[4]. Here the nepheline is largely altered to analcime. A more remarkable type is the 'lugarite' of Tyrrell (*loc. cit.*), in which nepheline and primary analcime together make up about 50 *per cent.* It contains idiomorphic purple augite with strong pleochroism

[1] Tyrrell, *G. M.* 1912, 70–73.

[2] J. F. Williams, *Ign. Rocks Ark.* (1890) 267–276; Washington, *Bull. Geol. Soc. Amer.* (1900) xi, 399, and *Journ. Geol.* (1901) ix, 615–617. The latter author gives to this type the name 'arkite.'

[3] Wolff, *Notes on the Petrography of the Crazy Mts, etc., Northern Transcontinental Survey* (1885); and Diller, *Bull.* 150 *U. S. G. S.* 197–200.

[4] Bailey, *Geology of Glasgow District* (*Mem. Geol. Sur. Scot.* 1911) 134–135; Tyrrell, *G. M.* 1912, 79–80, and *Q. J. G. S.* lxxii (1917) 105–107.

and very large crystals of red-brown barkevicite, together with labradorite, ilmenite, and apatite.

Of non-felspathic rocks we have already mentioned urtite as extremely rich in nepheline and so a leucocratic type (*i.e.* with dominant light minerals). The *ijolites* are melanocratic rocks, being rich in the dark minerals. They consist essentially of nepheline and pyroxene or amphibole, sometimes with

FIG. 18. NEPHELINE-BEARING ROCKS, U.S.A.; ×20.

A. Ijolite, Magnet Cove, Arkansas; composed of nepheline, augite, and deep brown melanite garnet (in irregular grains), with some pale biotite.

B. Theralite, Gordon's Butte, Crazy Mts, Montana. In addition to felspar (*f*) and nepheline (*n*), there is a group of sodalite crystals (*so*). The ferro-magnesian minerals are pale augite (*au*), bordered with bright green ægirine, and some biotite (*bi*), pale in the interior but deep brown at the border.

melanite, besides sphene or perovskite and amphibole. Examples from Magnet Cove, Arkansas[1], have augite and melanite (fig. 18, *A*), while those in the Bancroft district of Ontario[2] have hastingsite.

[1] Washington, *Bull. Geol. Soc. Amer.* (1900) xi, 400; *Journ. Geol.* (1901) ix, 618. This is the 'Ridge type' of Williams, *Ign. Rocks Ark.* (1890) 229–231.

[2] Adams and Barlow, *Geology of the Haliburton and Bancroft Areas* (*Geol. Sur. Can.*) 1910, p. 288.

CHAPTER V

DIORITES

The diorites are plutonic rocks of medium to coarse texture, consisting essentially of a soda-lime felspar and hornblende, with less important constituents. The family so defined cannot be regarded as a natural one, its members ranging in chemical composition from sub-acid to thoroughly basic. The gabbros (characterized by pyroxenes in place of hornblende) also include intermediate as well as basic rocks, and the distinction between the hornblende- and augite-bearing types is rather an artificial one. It was established before the strong tendency of augite to pass over into hornblende was thoroughly appreciated: later research has shown the certainty of some, and the possibility of many, of the rocks which have been termed diorites being really amphibolized pyroxenic rocks.

The more acid diorites contain free silica (*quartz-diorites*), and, except for the smaller proportion of quartz and the nature of the felspars, do not differ much from the hornblende-granites. They may have biotite in addition to hornblende (*quartz-mica-diorites*), or in some cases augite. In the *diorites* proper, without quartz, mica is not common, but the hornblende may be accompanied by augite or sometimes enstatite. The hornblende is more abundant relatively to the felspar than in the preceding types, and some of the more basic diorites consist chiefly of hornblende. These are the 'amphibolites' of some authors. In some types olivine enters as a constituent (*olivine-diorites*).

Constituent minerals. The felspar of the diorites is *andesine* or *labradorite*, or exceptionally a more basic variety. The twin-lamellation on the albite type is often accompanied by pericline- or Carlsbad-twinning (fig. 3, *B*). In the quartz-diorites especially the crystals frequently show between crossed nicols a marked zonary banding, the central and marginal portions of a crystal often giving widely different extinction-angles, and the successive layers growing more acid from within

outwards (fig. 3, *A*). In natural light the zones of growth may be indicated by the disposition of fluid-pores, minute scales of hæmatite, or other inclusions. The crystals are often clouded by a fine dust and may also furnish by their alteration scales of colourless mica, grains of epidote, calcite, *etc.* A little *orthoclase* may be present as an accessory, behaving in the quartz-diorites as in granites, while in simple diorites it occurs interstitially.

The *hornblende*, when idiomorphic, shows the prism-faces and usually the clinopinacoid, and terminal planes are often present. Twinning is common, and the prismatic cleavage is always well pronounced. In the quartz-diorites the mineral, usually in imperfect crystals, is green, as in granites; in diorites it has brownish green or greenish brown colours; and in the most basic types the original hornblende approaches the deep brown of 'basaltic hornblende.' Pale colours result from bleaching, or are found in secondary outgrowths of the brown crystals[1], and these are green rather than brown (fig. 20, *C*).

The deep brown *biotite* of the diorites occurs in idiomorphic flakes, or sometimes intergrown with hornblende. It is usually not rich in inclusions. It becomes green only by partial decomposition.

When *augite* is present, it is of a variety sensibly colourless in slices. If idiomorphic, it shows the octagonal cross-section due to equal development of the pinacoids and prism-faces, with good prismatic cleavage and not infrequently lamellar twinning parallel to the orthopinacoid. A not uncommon feature in diorites is a parallel growth of augite and hornblende, a crystal-grain of the former mineral constituting a kernel, round which a shell of brown hornblende has grown, and this seems to occur specially in the neighbourhood of grains of iron-ore (fig. 20, *A*). This must be distinguished from another phenomenon frequent in the augite-bearing diorites, *viz.* the conversion of augite into brown hornblende as a secondary change. This process usually begins at the margin of a crystal or grain, but proceeds irregularly, showing a very intricate boundary between the two minerals and often ragged scraps of one enclosed by the other (fig. 19, *A*). When the conversion

[1] Compare Teall, *Brit. Petr.* pl. VI.

is complete, the secondary hornblende can be distinguished from original only by inference, as, *e.g.*, when it shows the external form of augite. In both phenomena the augite and hornblende have their plane of symmetry and longitudinal axis in common, and in longitudinal sections both extinguish on the same side of the axis.

The *quartz* of quartz-diorites has the same general characters as that of granites.

The *olivine* which occurs in some basic diorites is often in rather rounded crystals enclosed by the hornblende. It is easily recognized by its high refractive index and very strong double refraction. The mineral is readily altered into serpentine, carbonates, and especially pale fibrous amphibole, the last often grown in crystalline continuity with adjacent original hornblende.

Among the iron-ores *magnetite* is the most usual, but *ilmenite* is also found. Common accessories in some varieties are *zircon* and *sphene* in characteristic crystals. *Apatite* is general, and in some basic diorites abundant: in the coarse-grained rocks it sometimes builds rather large prisms.

Structure. The structure of the dioritic rocks is variable. In the quartz-diorites the mutual relations of the minerals are those noticed in granites, though sometimes a part of the felspar has crystallized before the ferro-magnesian minerals. A micrographic intergrowth of quartz and felspar is not infrequent. Many of the quartzless diorites also follow what may be called the normal order of crystallization, but a different type of structure, though connected by transitions with the preceding, is found in other varieties. Here the plagioclase has crystallized earlier, or at least ceased to crystallize earlier, than the bisilicates; so that the dominant felspar presents idiomorphic outlines to the hornblende and (if present) augite. These latter may wrap round, or even enclose, the felspar crystals, giving an 'ophitic' structure identical with that described below as characteristic of the dolerites. This is found more or less markedly in many of the more basic diorites, and is especially common in rocks in which the hornblende is in

great part derivative after augite, though original hornblende moulded on felspar is also found.

Pegmatoid and aplitic structures are less common in this family than in the granites and syenites.

Leading types. Of the *quartz-diorites* the most acid type, constituting a connecting link with the granites, is 'tonalite,' typically developed in the Adamello Alps, on the border of Italy and the Tirol. It has also points in common with the monzonites. The dominant felspar is a striated plagioclase often showing zonary banding, and with a strong tendency to idiomorphic outlines; but there is frequently some orthoclase in addition, in irregular crystal-plates moulded on or enclosing the triclinic felspar. Biotite is the most constant coloured element, but hornblende is also abundant. The mutual relations of the two are variable, and both may enclose the plagioclase. Interstitial quartz is fairly plentiful and patches of magnetite are often prominent. These Alpine rocks often show signs of crushing (Chapter XXIII).

The Palæozoic intrusions of the Scottish Highlands afford many examples of quartz-diorites. The most acid are of the tonalite type, and graduate into hornblende-granites, while the less acid varieties pass into quartzless diorites[1]. The principal constituent minerals are green hornblende, biotite and sometimes augite, zoned plagioclase, often with a small amount of orthoclase, and quartz. Biotite is usually subordinate to hornblende, but there are some quartz-mica-diorites: *e.g.* Glen Derry, north of the Dee (with oligoclase-andesine). Augite is less frequently found in these rocks than in the more basic diorites, and is often partly converted to hornblende (fig. 19, *A*).

The intrusion of Criffel, in Galloway, also has a quartz-diorite as its prevalent type[2]. In Co. Wicklow, to the east

[1] See Memoirs of *Geol. Survey Scot.*, especially *Geology of Blair Atholl* (1905) 112–113, *Geology of Oban and Dalmally* (1908) 84–85, *Geology of Braemar* (1912) 75–80. On the rocks of Garabal Hill, near Loch Lomond, see Dakyns and Teall, *Q. J. G. S.* (1892) xlviii, 104–120, and Wyllie and Scott, *G. M.* 1913, 499–508, 536–545.

[2] Teall, *Silur. Rocks Scot.* (*Mem. Geol. Sur.* 1899) 607–621.

of Rathdrum, occur quartz-diorites and quartz-mica-diorites which in some particulars approximate to the granites, subordinate orthoclase accompanying the dominant triclinic felspar. The other minerals are pale green hornblende, ragged flakes of biotite, abundant quartz, apatite, and sometimes a little colourless augite[1].

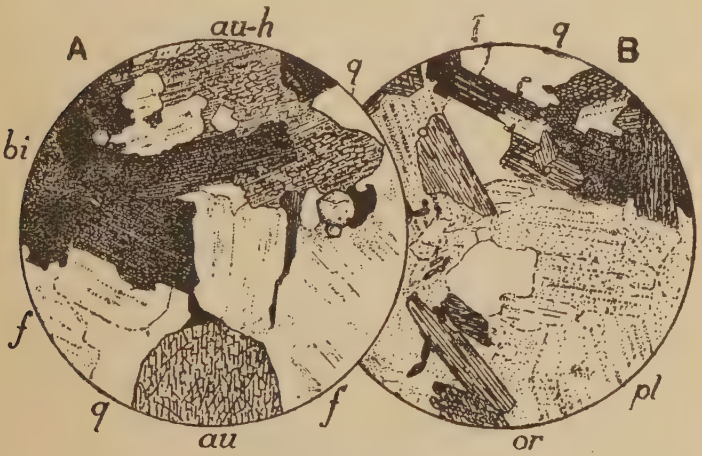

FIG. 19. QUARTZ-DIORITES; ×20.

A. Beinn Cruachan, Argyllshire. The felspar (*f*) is strongly zoned between crossed nicols, but approximates to the composition of oligoclase. The ferro-magnesian minerals are biotite (*bi*) and colourless augite (*au*), the latter partly transformed to light green hornblende (*au-h*). Magnetite, apatite, and sphene are also present, and quartz (*q*) is the latest product of crystallization.

B. Near Grouse Lake, Sierra Nevada ('Granodiorite'): composed of green hornblende and plagioclase felspar (*pl*), with some biotite, orthoclase (*or*), quartz (*q*), sphene, magnetite, and apatite.

In the United States, as in Britain, numerous rocks belonging here have been designated granite, or sometimes granite-diorite. A type with subordinate potash-felspar, largely de-

[1] Hatch, *G. M.* 1889, 262–263.

veloped in the Sierra Nevada of California, has been styled 'granodiorite,' and is regarded by Lindgren[1] as intermediate between true quartz-diorite and quartz-monzonite (fig. 19, *B*).

A *mica-diorite*, without quartz, is not a common type. It is found as a local modification of biotite-granite between Carrick Mt and Arklow, in Wicklow. Sir Jethro Teall has figured a good example from Pen Voose in the Lizard district, Cornwall[2]. This consists essentially of felspar and a reddish brown mica with only quite subordinate green hornblende and accessory sphene. From Allt a' Mhuillin, south of Lochinver, Sutherland, the same author notes a mica-diorite with interstitial felspar. Mica-diorite occurs also in the complex of Garabal Hill, near Loch Lomond.

The simple *hornblende-diorites*, without quartz, are of more frequent occurrence. The chief varieties arise from varying relative proportions of hornblende and felspar. The hornblende, especially in the more melanocratic rocks, is of a browner colour than that of the quartz-diorites. In the Highlands good examples are found in the Garabal Hill complex, in Glen Doll, near Clova (including a variety with porphyritic hornblende), Glen Tilt (Perthshire), and Strathdon (Aberdeenshire). Sills of diorite with well shaped crystals of hornblende occur near Inchnadamph in Sutherland (fig. 20, *B*).

Diorites are found again in Warwickshire and other parts of the Midlands. In the rock of Atherstone, Hartshill, the brown hornblende is in part idiomorphic towards the turbid felspar; but part of it, on the other hand, is derived from a colourless augite, and a kernel of the latter mineral sometimes remains unchanged. Grains of magnetite are present, and abundant prisms of apatite. Allport[3] noted also olivine, pseudomorphed by carbonates, *etc.* Rather coarse-grained diorites are met with in the curious complex of igneous rocks

[1] *A. J. S.* (1897) iii, 308–312; see also Turner, 17*th Ann. Rep. U.S. G. S.* (1896) 636–637, pl. XLII, A.

[2] Teall, *Brit. Petr.* pl. XXXII, fig. 1; XLVII, fig. 3.

[3] *Q. J. G. S.* (1879) xxxv, 637–641. Some of the rocks included as diorites by this author would now be classed with the lamprophyres: see below, Chap. XI; compare Watts, *Pr. Geol. Ass.* (1893) xv, 394–396.

in the Malvern district, and a small mass occurs at Brazil Wood in Charnwood Forest[1].

A colourless augite accompanies the hornblende in not a few of the rocks already mentioned, and in some types is sufficiently

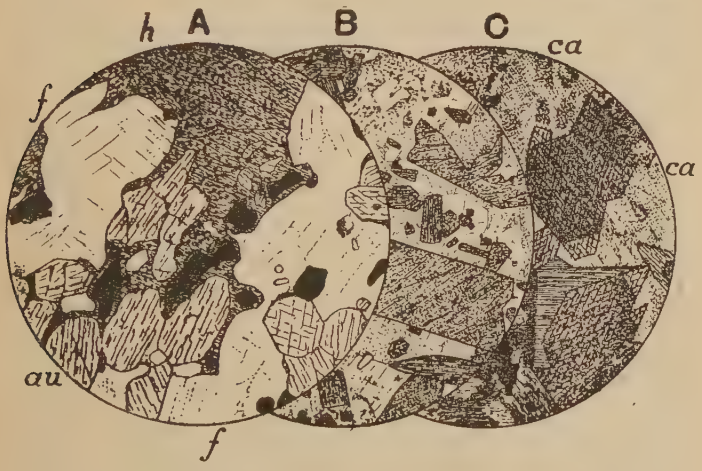

Fig. 20. Basic Diorites; ×20.

A. Augite-Diorite, Delancy Hill, Guernsey; with idiomorphic crystals of pale augite (*au*). The brown hornblende (*h*) is allotriomorphic, and is often interposed between augite and magnetite.

B. Diorite, near Inchnadamph, Sutherland; with idiomorphic hornblende.

C. Secondary outgrowth from hornblende crystals in altered diorite, near Llanerchymedd, Anglesey. The felspar is largely replaced by calcite (*ca*), into which project the new growths of green hornblende. These are developed partly on the clinopinacoid faces of the primary brown crystals, partly on the terminal planes.

important to warrant the name *augite-diorite*. The augite often occurs as a core to brown primary hornblende, with the usual crystallographic relation (fig. 20, *A*). Good examples occur in the Channel Islands. One from the Ropewalk Quarry, Guernsey,

[1] Hill and Bonney, *Q. J. G. S.* (1878) xxxiv, 224.

contains also large crystals of a rhombic pyroxene, converted to bastite.

Some of the more melanocratic diorites contain, or have contained, olivine, and these *olivine-diorites* graduate into hornblende-peridotites. It is often difficult to verify the former presence of olivine, when both this mineral and the felspar are totally destroyed. Their place is taken largely by secondary hornblende, grown as a fringe to the primary crystals but distinguished by its different colour. Excellent illustrations are found in the rocks of Llanerchymedd in Anglesey[1] (fig. 20, *C*). Other olivine-bearing diorites occur near Clynog-fawr in Caernarvonshire[2]. Here the hornblende forms ophitic plates, and is probably in part derived from augite. The same remark applies to certain rocks at Penarfynydd[3] in the Lleyn peninsula, where both ophitic and idiomorphic augite may be seen partly converted into brown hornblende. Some thoroughly basic dioritic rocks, very like those of Anglesey, occur in the Lake District, *e.g.* at Little Knott[4], White Hause, and Great Cockup[5], in the Skiddaw district. The rock at the first-named locality shows beautifully the pale fringes of hornblende which form a new outgrowth from the original crystals. Some of these Welsh and Cumbrian diorites are practically pure *hornblende-rocks*, the mineral being mainly primary but partly derivative. Rocks composed wholly of primary hornblende occur only as local facies of more normal diorites.

[1] Bonney, *Q. J. G. S.* (1881) xxxvii, 137–139; (1883) xxxix, 254–256; Harker, *G. M.* 1887, 546–552.

[2] *Bala Volc. Ser. Caern.* 102–106.

[3] *Ibid.* 92–97.

[4] Bonney, *Q. J. G. S.* (1885) xli, 511–513, pl. xvi, fig. 2.

[5] Postlethwaite, *Q. J. G. S.* (1892) xlviii, 510.

CHAPTER VI

GABBROS AND NORITES

no glass

The gabbros and their allies are holocrystalline rocks, typically of plutonic habit, in which the essential constituents are a lime-soda-felspar and a pyroxene. Of intermediate to thoroughly basic character, they correspond partly with the diorites; but the more acid, and especially the quartz-bearing types, are less represented in the pyroxenic than in the hornblendic series. According to the dominant pyroxene, we recognize *gabbro* proper (euphotide of Haüy) with diallage or augite, and *norite* (also called hypersthenite[1]) with a rhombic pyroxene. A few of the more acid rocks contain free silica (*quartz-gabbro* and *quartz-norite*). In most of the more basic varieties olivine becomes a characteristic mineral (*olivine-gabbro* and *olivine-norite*). The majority of the rocks in this family contain more or less olivine, but the mineral may be present or absent in different specimens of the same mass.

diopside

The gabbros and norites, indeed, show considerable variations in mineralogical constitution in parts of one mass, and some of the special types are probably to be regarded as merely local modifications. Thus, by the failure of one or other of the chief constituents of a gabbro we may have an almost pure *felspar-rock* (labrador-rock, anorthosite) or *pyroxene-rock* (pyroxenite, including diallage-rock, *etc.*). By the disappearance of pyroxene in an olivine-gabbro we have the so-called *troctolite* (Ger. Forellenstein), composed essentially of felspar and olivine: with abundant olivine and diminishing felspar we have transitions to the succeeding family of peridotites.

The name *eucrite* is applied to rocks in which the felspathic element is anorthite. The abundant felspar is associated with pyroxene, often both monoclinic and rhombic, with or without olivine.

[1] In many of the 'hypersthenites' of the older writers the supposed hypersthene is only a highly schillerized diallage.

Inclusions + cavities

all ig ned within a crystal;

poikilitic structure

We shall briefly notice in addition certain basic rocks, *essexites* and *teschenites*, which have decidedly alkaline affinities.

Constituent minerals. The felspar of the gabbros and norites proper is *labradorite*, while that of the eucrites is *anorthite*. It builds large irregularly-shaped plates with, as a rule, rather broad lamellæ (albite-twinning) often crossed by fine pericline-striation. The lamellæ not infrequently have something of a wedge-shape. A crystal with broad albite lamellæ, if cut nearly parallel to the brachypinacoid, may appear untwinned. It is not safe to assume that the most constant twin-lamellation necessarily corresponds with the albite law: the felspar of some rocks of this family has pericline-twinning alone or predominant. The zonary structure, so general in many of the diorites, is not characteristic of the gabbro family. Besides fluid-pores and inclusions of earlier products of crystallization, the felspars often show more or less marked schiller-structure. Any plagioclase more acid than labradorite is exceptional, and so is the occurrence of *orthoclase*.

The *augite* of the gabbros builds irregular crystal-plates and wedges of very pale green or light brown colour. Besides the usual prismatic cleavage, an orthopinacoidal cleavage and *diallage*-structure are very common (fig. 25, *A*), or instead of this there is sometimes a very minute striation parallel to the basal plane. Combined with the common orthopinacoidal twinning, this produces a characteristic 'herring-bone' appearance (fig. 21, *A*). The basal striation will be conveniently called the *salite* structure. Both this and the diallagic may occur inconstantly, and both may be found in the same crystal (fig. 21, *B*). Decomposition of the augite gives rise characteristically to a scaly or fibrous aggregate of chlorite and serpentine with other products. Another common alteration is the conversion to hornblende, which may be light green and fibrous (uralite) or deep brown and compact.

In the rocks here included original *hornblende* is found only as an occasional accessory: a deep brown variety occurs in some norites. Brown *biotite* may also occur as a minor accessory

(*e.g.* Carrock Fell; St David's Head), and it may be intergrown with augite (Stanner Rock, near New Radnor[1]).

The rhombic pyroxenes, *bronzite* and *hypersthene*, occur as accessory minerals in rather rounded but idiomorphic crystals, while in the norites they often show but little crystal-outline. A schiller-structure is common in many norites and

FIG. 21. GABBROS; ×20.

A. Quartz-Gabbro, Carrock Fell, Cumberland: composed of augite, labradorite, and a little altered biotite and clear quartz. The augite has the salite structure in conjunction with twinning on the ortho-pinacoid, giving the 'herring-bone' appearance.

B. Gabbro, Glen an t-Suidhe, Arran: showing ophitic habit of augite. Almost the whole of this mineral in the field belongs to a single crystal, which has in places a strong schiller-striation, partly of the diallage type (*di*) and partly of the salite type (*sa*).

gabbros (fig. 22, *A*). The most usual alteration gives distinct pseudomorphs of the serpentinous mineral bastite. This is pale green or yellowish, with slight pleochroism and low polarization-tints. The pseudomorph is built of little fibres arranged longitudinally, and is traversed by irregular cracks which the fibres do not cross. The individual fibres give straight

[1] Cole, *G. M.* 1886, p. 221, fig. 3.

extinction, but, as there is a slight departure from perfect parallelism in their arrangement, a very characteristic appearance is offered. The rhombic pyroxenes also show uralitization.

When *olivine* is present, it builds imperfect crystals or rounded grains, colourless in slices. Where it adjoins felspar, it is often bordered by a rim of hypersthene (fig. 22, *B*). The olivine sometimes has schiller-inclusions. Its most characteristic mode of alteration is 'serpentinization.' This process begins round the margin of the crystal-grain and along the usually irregular network of cracks which traverses it. Along these, as a first stage, strings of granular magnetite separate out. The immediate walls of the cracks are converted into pale greenish or yellowish fibrous serpentine, the fibres set perpendicularly to the crack, and giving straight extinction and low polarization-tints. At this stage the meshes of the network are occupied by unaltered remnants of olivine. These may be subsequently altered to serpentine, which is of a different character from that first formed, being often sensibly isotropic[1]. As a last stage, some of the magnetite may be reabsorbed, giving a deeper colour to the serpentine pseudomorph. The change from olivine to serpentine involves an increase of volume, which gives rise to numerous radiating cracks traversing adjacent minerals. These cracks are injected with serpentine, usually isotropic (fig. 24).

Where primary *quartz* occurs in gabbros, *etc.*, it has the same properties as that in granites. Usually it forms part of a micrographic intergrowth.

Original iron-ores occur only sparingly in some rocks of the gabbro family, but sometimes become abundant. They are *ilmenite* (with leucoxene as a decomposition-product) and *magnetite*. Alteration product of ilmenite.

The *apatite* builds the usual hexagonal prisms or sometimes short rounded grains (fig. 22, *A*). In other accessories the rocks are usually very poor, zircon and original sphene being absent.

[1] This effect is possibly due to the overlapping of a crowd of minute fibres or scales without any definite orientation.

Structure. In texture the rocks of this family vary from medium to coarse grain. In some the individual crystals of felspar and pyroxene attain a large size, and they are then, as a rule, strongly affected by schiller-structures. Porphyritic structure is very rarely met with in the gabbros and norites.

Apatite, iron-ores, and olivine, when present, are the earliest minerals, and are clearly idiomorphic, while in the

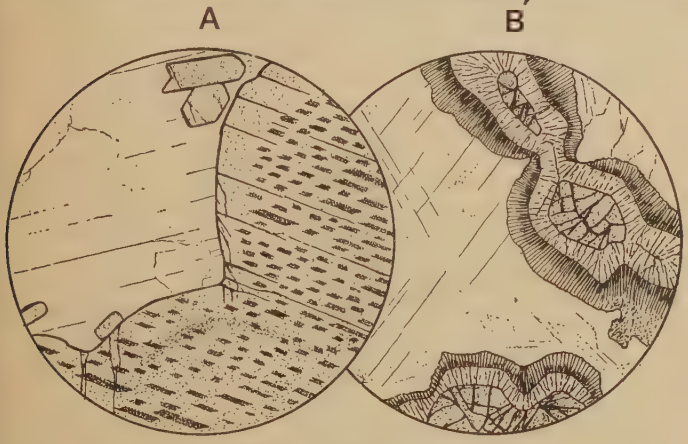

FIG. 22. NORITES; ×20.

A. Labrador coast. The rock consists essentially of labradorite and hypersthene, the latter showing pronounced schiller-structure: there are also conspicuous crystals of apatite (upper part).

B. Risör, Norway: showing corona-structure. The olivine is surrounded by a double border, the inner layer consisting of enstatite and the outer largely of fibrous hornblende.

special types containing orthoclase and quartz these minerals have always crystallized last. But as regards the two main constituents, augite and plagioclase, the mutual relations are not always the same. In many gabbros the felspar is more or less distinctly embraced by the augite or diallage, but if this character becomes marked there are often other features which indicate a transition to the dolerite type. The more

typical gabbros are often thoroughly hypidiomorphic; or the augitic constituent, especially if very abundant, may be embraced by the felspar. When a rhombic pyroxene enters, it is idiomorphic towards the monoclinic, and usually towards the felspar also.

An interesting variety of structure arises from the circumstance that olivine, crystallized at an early stage, has often been partly redissolved with the production of a rhombic pyroxene. There may then be, surrounding a corroded grain of olivine, a border of enstatite or hypersthene as an aggregate of small crystal-grains. This *corona-structure* has sometimes a very regular development, and there may even arise two or three successive borders of different mineralogical composition (fig. 22, *B*). Similar structures in other cases seem to be due rather to reactions between contiguous minerals in the rock subsequent to its consolidation (*'reaction-rims'*)[1].

Primary gneissic banding is met with in some rocks of this family, and may be associated with a parallel arrangement of the felspar crystals. The structure is strongly developed in certain gabbros in Skye[2], which show lighter and darker bands (more felspathic and more pyroxenic), with some seams composed mainly of the dark minerals and especially rich in titaniferous iron-ore.

Leading types. We begin with the rather exceptional rocks in which free silica has been developed as an original constituent. A good example of a *quartz-gabbro* is that of Carrock Fell, in Cumberland[3] (fig. 21, *A*). The essential constituents are a somewhat basic variety of labradorite and an augite with basal striation. Imperfect prisms of enstatite also occur, and there is often a parallel intergrowth of the two pyroxenes. The augite is often converted into a greenish fibrous hornblende and the enstatite into bastite. Biotite is found

[1] Bayley, *Amer. Journ. Sci.* (1892) xliii, 515–518; *Journ. of Geol.* (1893) i, 702–710; Williams, *Bull. No.* 28 *U. S. Geol. Sur.* (1886), with plates.

[2] Geikie and Teall, *Q. J. G. S.* (1894) l, 645–656, pl. xxviii; Harker, *Tertiary Igneous Rocks of Skye* (*Mem. Geol. Sur.* 1904) 117–120.

[3] *Q. J. G. S.* (1894) l, 316–318, pl. xvii; (1895) li, 125. The rock has been termed hypersthenite, but the rhombic pyroxene is always subordinate to the monoclinic and sometimes wanting.

locally. Magnetite and ilmenite occur, sometimes in evident intergrowths. Quartz is found partly in interstitial grains but chiefly in micrographic intergrowth with felspar, some of which is orthoclase. The rock varies much, the central part of the mass being rich in quartz, while the margin is highly basic, free from quartz and remarkably rich in iron-ores and apatite.

The coarse intrusive masses near St David's Head, in Pembrokeshire[1], include rocks which vary between quartz-gabbro and *quartz-norite*. Augite (with salite structure) and a rhombic pyroxene (often replaced by bastite) occur together, sometimes in parallel intergrowth. The felspars are zoned, ranging from an acid labradorite to oligoclase, and there is some orthoclase, which enters into micrographic intergrowth with the quartz. These rocks are intimately associated with more basic types (biotite-norite).

Of simple *gabbros* good examples are found in the neighbourhood of Ballantrae, Ayrshire. They are often of coarse grain. The pyroxenic constituent is sometimes a diallage (Lendalfoot), sometimes a colourless augite partly converted to brown hornblende. Coarse gabbros from Guernsey (Bellegrève) also show well this conversion of colourless augite into brown or greenish brown compact hornblende, the process being seen in every stage. In some slides no augite remains, and, without comparison with other specimens, the rock might be taken for a true diorite, but the hornblende is probably all derivative. The ferro-magnesian silicates are often moulded on the felspar, which is of a basic variety. Of the Tertiary gabbros of the western isles of Scotland few are free from olivine: examples are found in Skye (N.W. of Broadford).

In Scotland *norites* occur in Aberdeenshire, Banffshire, and other districts. One from Towie Wood, near Ellon, consists essentially of labradorite and a rhombic pyroxene, which is pale and without schiller-structure (fig. 23, *B*); while others from the same neighbourhood contain in addition augite, hornblende, and biotite. Examples from near Lochinver, Sutherland, contain brown hornblende, and the felspar is not

[1] Elsden, *Q. J. G. S.* (1905) lxi, 584–592, and (1908) lxv, 273–294, with plates.

always of a very basic variety (fig. 23, *A*). The Tertiary plutonic rocks of Britain include few norites, though beautiful examples, with and without accessory augite, are found near Glenloig, Glen an t-Suidhe, Arran[1]. A norite from near Banff has a deep brown strongly schillerized hypersthene like the well-known Labrador occurrence (fig. 22, *A*).

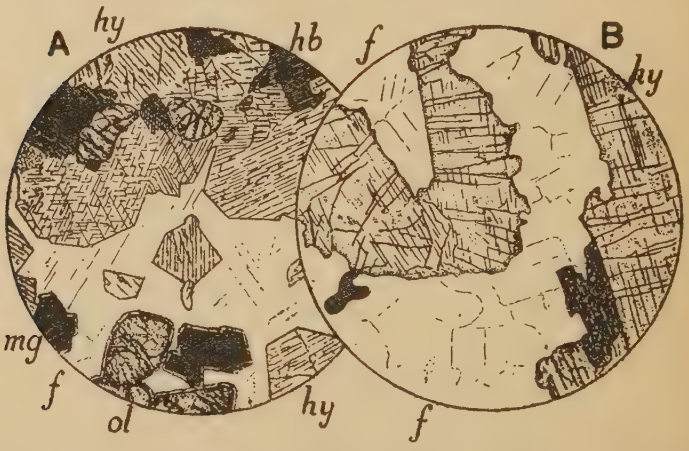

FIG. 23. NORITES, SCOTLAND; ×20.

A. Badenaban, near Lochinver, Sutherland. The constituents are magnetite (*mg*), olivine (*ol*), hypersthene (*hy*) often with intergrowths of augite, deep brown hornblende (*hb*), and clear felspar (andesine) (*f*). The magnetite and olivine, where they adjoin felspar, are bordered by a narrow fringe of green pyroxene.

B. Towie Wood, Ellon, Aberdeenshire. Composed essentially of hypersthene and felspar (labradorite), with accessory magnetite and biotite, or in other parts of the slice brown hornblende.

By far the most widely distributed among the rocks of this family are the *olivine-gabbros*. Here belong most of the basic plutonic rocks of Skye[2], Mull[3], and Arran[4]. The olivine is

[1] *Geol. N. Arran Scot.* (*Mem. Geol. Sur.* 1903) 108.

[2] *Tert. Ign. Rocks Skye* (*Mem. Geol. Sur.* 1904) ch. viii.

[3] Judd, *Q. J. G. S.* (1886) xlii, 49–89, pl. iv.

[4] The Arran rocks are mostly amphibolized and have usually been termed diorites.

frequently rather rich in iron, and gives rise to much magnetite-dust as an alteration-product. Original iron-ores and apatite may or may not be present. The felspar is usually a labradorite, and this, rather than the pyroxene, tends to assume crystal-outlines, the structure of the rock being often subophitic. The augite, as a rule, has a striation parallel either to the basal plane or to the orthopinacoid, with more or less marked schillerization. Rhombic pyroxene is only an exceptional accessory constituent.

The unaltered gabbros of the Lizard district, Cornwall, according to Dr Flett[1], always contain olivine. The felspar is labradorite crowded with minute black inclusions. The pyroxene is a pale diallagic augite, but hypersthene sometimes occurs as narrow coronas round the olivine, and there may be a little brown hornblende associated with the diallage. Many of the rocks have been altered by dynamic metamorphism, the pyroxene being amphibolized and the felspar replaced by a 'saussuritic' aggregate.

The *eucrite* type, in which the felspathic element is consistently of a very basic species (anorthite or bytownite), usually differs also in other particulars from true gabbros. Among the British Tertiary rocks eucrites are well developed in the Isle of Rum[2], Ardnamurchan, and the Carlingford district[3]. In these rocks rhombic and monoclinic pyroxenes usually occur together, and sometimes are intimately intergrown. Olivine is present or absent in different varieties. This mineral, as well as the pyroxenes, is not infrequently moulded on the felspar crystals.

The plagioclase-felspar-rocks known as *anorthosites* must be regarded as peculiar members of the gabbro family. Such rocks occupy extensive tracts in the Lake Superior region[4], the Adirondacks (N.Y.)[5], and the Province of Quebec. They

[1] *Geology of the Lizard* (*Mem. Geol. Sur.* 1912) 86–87.

[2] *Geology of the Small Isles* (*Mem. Geol. Sur. Scot.* 1908) 97–100.

[3] Von Lasaulx, *Sci. Proc. Roy. Dubl. Soc.* (1878) ii, 31–33; Sollas, *Tr. Roy. Ir. Acad.* (1894) xxx, 482–487.

[4] Lawson, *Bull. No.* 8 *Geol. and Nat. Hist. Sur. Minn.* (1893) (Minnesota); Coleman, *Journ. Geol.* (1896) iv, 907–911 (Rainy Lake region).

[5] Kemp, *Bull. Geol. Soc. Amer.* (1894) v, 215–216; *Geology of Moriah and Westport, Bull. N.Y. State Mus.* (1895) iii, 337.

are of coarse grain, and consist essentially of labradorite, or exceptionally a more calcic variety of plagioclase[1]. A little augite, of faint violet-brown tint in sections, is the only other original mineral, and this occurs both in grains and as minute parallel interpositions in the felspar. In Britain a purely felspathic rock is known only as a local variety of a gabbro or eucrite.

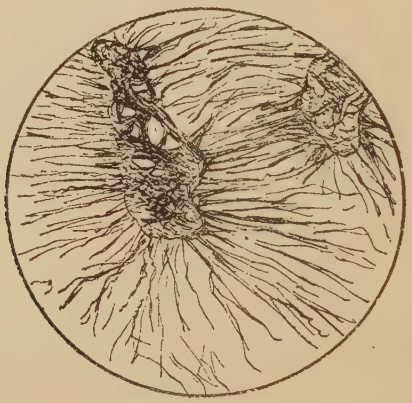

FIG. 24. LABRADORITE-OLIVINE-ROCK (TROCTOLITE), COVERACK COVE, CORNWALL; ×20.

The olivine is almost wholly converted into serpentine (a few clear granules remaining), and the consequent expansion has caused radiating fissures through the surrounding felspar.

When the pyroxene in an olivine-gabbro is reduced to a vanishing amount, we have the type known as *troctolite* (Ger. Forellenstein), consisting essentially of an aggregate of labradorite in which grains of olivine are embedded. A good example occurs near Coverack in the Lizard district[2] (fig. 24).

Contrasted with the anorthosites are the *pyroxenites*, in

[1] The mineralogical term 'anorthose' (Delesse), from which anorthosite is named, is synonymous, not with anorthite, but with plagioclase generally.

[2] Flett, *Geology of the Lizard* (*Mem. Geol. Sur.* 1912) 85-86; Teall, *Brit. Petr.* pl. VIII, fig. 2.

which felspar is lacking. Such a rock may consist of a rhombic or a monoclinic pyroxene or of the two together, as in the bronzite-diopside-rocks of North Carolina and Maryland (Webster type)[1]. An enstatite-rock has been described from Marico in the Transvaal[2]. Some British gabbros pass locally into a diallage-rock, as at Lendalfoot in Ayrshire[3] (fig. 25, *A*), and in the complex of Garabal Hill, near Loch Lomond[4], is a

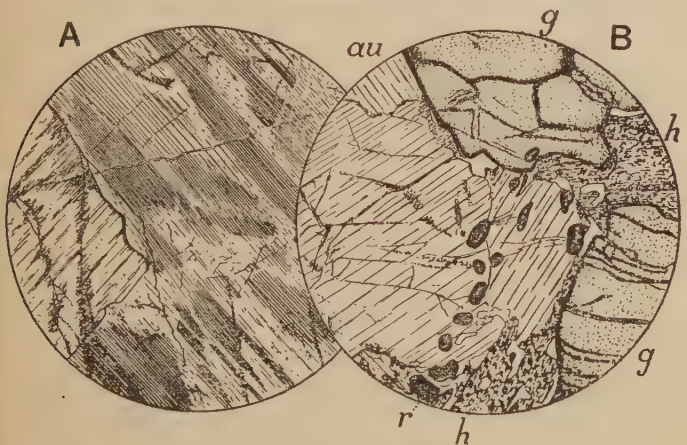

FIG. 25. PYROXENIC ROCKS, SCOTLAND; ×20.

A. Diallage-rock, Lendalfoot, Ayrshire: showing schiller-striation parallel to the orthopinacoid. In the crystal to the left there is only an incipient development of this structure.

B. Eclogite, near Glenelg, Invernessshire: composed of garnet (*g*), pale augite (*au*), and green hornblende (*h*), with grains of deep brown rutile (*r*) and small interstitial patches of quartz.

diallage-enstatite-rock almost wholly converted to brown hornblende.

Of different significance are the pyroxene-garnet-rocks

[1] G. H. Williams, *Amer. Geol.* (1890) vi, 40–49, pl. II, fig. 2.
[2] Maskelyne, *Phil. Mag.* (1879) vii, 135–136; Hatch, *Tr. Geol. Soc. S. Afr.* (1904) vii, 4.
[3] Bonney, *Q. J. G. S.* (1878) xxxiv, 778–780.
[4] Wyllie and Scott, *G. M.* 1913, 500–505.

named *eclogites*, which, with the chemical composition of gabbros, present a mineralogical constitution quite peculiar. They are found sparingly in regions of gneissic rocks, and doubtless represent deep-seated intrusions of basic magma crystallized under conditions of stress. Examples have been described from the Lewisian series in the district of Loch Duich[1] and Glenelg[2] (fig. 25, *B*), on the southern border of Ross[3], and near Pettigo in Co. Donegal[4]. Various accessory minerals are present in the different occurrences. There are also hornblende-eclogites (or 'garnet-amphibolites') near Loch Maree[5] and in the district of Scourie and Loch Laxford in Sutherland[6].

In the *essexites*, sometimes regarded as a distinct family, the dominant labradorite felspar is accompanied by a variable amount of orthoclase, and sometimes by a little nepheline or sodalite. Olivine is usually present, and the other ferro-magnesian minerals may include augite, hornblende, and biotite in various relative proportions, a purplish titaniferous augite being the most usual. The iron-ore is titaniferous, and apatite is rather abundant. Examples are found among the Carboniferous intrusions of Scotland. One from Lennoxtown[7], in Stirlingshire, consists of about equal parts of purple augite, olivine, and a basic plagioclase, besides other minerals.

In the *teschenites* the relatively alkaline composition is marked especially by the occurrence of analcime in greater or less amount. This mineral, always allotriomorphic, seems to be sometimes primary, sometimes secondary after nepheline, and it is difficult to draw a line between the teschenites and the theralites (p. 61). Numerous examples are found in the Carboniferous districts of Scotland: *e.g.* on Inchcolm in the Forth[8] and at Lugar in Ayrshire[9].

[1] Teall, *Min. Mag.* (1891) ix, 217–218.
[2] Peach, *Geology of Glenelg* (*Mem. Geol. Sur. Scot.* 1910) 32–35.
[3] Flett, *Summary of Progress Geol. Sur.* for 1905, 160–166.
[4] Cole, *Tr. Roy. Ir. Acad.* (1900) xxxi, 457–458, pl. xxvi, fig. 6.
[5] Bonney, *Q. J. G. S.* (1880) xxxvi, 105–106.
[6] Harker, *G. M.* 1891, 171–172.
[7] Bailey, *Geology of Glasgow District* (*Mem. Geol. Sur. Scot.* 1911) 128–131.
[8] Campbell and Stenhouse, *Tr. Geol. Soc. Edin.* (1908) ix, 126–128. Compare Teall, *Brit. Petr.* (1888) pl. xxii, fig. 1 (Car Craig).
[9] Tyrrell, *Q. J. G. S.* (1917) lxxii, 98–103.

CHAPTER VII

PERIDOTITES (INCLUDING SERPENTINE-ROCKS)

The peridotites, named from their richness in olivine (peridote), are plutonic rocks of ultrabasic composition. The extreme type, *dunite*, consists exclusively of olivine with a subordinate amount of some spinellid mineral. Where other ferro-magnesians enter, we may recognize *enstatite-peridotites*, *augite-peridotites*, *hornblende-peridotites* (sometimes with biotite), and *garnet-peridotites*, with intermediate links.

For so small a group a needless multiplicity of names has been created. The simple olivine-rock is the 'dunite' of Hochstetter. With the addition of enstatite we have the 'saxonite' of Wadsworth[1], 'harzburgite' of Rosenbusch; with diallage, 'wehrlite'; with both rhombic and monoclinic pyroxenes, 'lherzolite'; with garnet, 'eulysite'; *etc.*

All these are typically non-felspathic; but we must also assign to the peridotite family rocks which, with preponderant olivine and various other ferro-magnesian minerals, contain also a limited proportion of felspar. Through these varieties there are transitions to the eucrites, norites, gabbros, and diorites. The felspar is always of a calcic kind. Anorthite, in respect of its low silica-percentage and total defect of alkalies, is an ultrabasic mineral equally with olivine; and we shall recognize especially a distinct type of olivine-anorthite-rock, *allivallite*, with varying proportions of the two minerals.

Finally, there are rocks rich in olivine which have decided alkaline affinities, and these will be distinguished under the name *picrite*[2].

[1] *Lithological Studies* (1884, Camb., Mass.). This work contains many descriptions of peridotites and meteorites, with a number of useful coloured plates.

[2] This accords with the original usage of the name by Tschermak: Rosenbusch and others have diverted it to the augite-peridotites.

Many of the *meteorites* ('stony meteorites' as distinguished from meteoric irons) have a mineral composition allied to that of the terrestrial peridotites, but often with special accessory minerals and peculiar structures[1].

In consequence of the unstable nature of their principal constituent mineral, the peridotites are very readily decomposed, and most of the *serpentine-rocks* have originated in this way.

Constituent minerals. The *olivine*, if not so abundant that its crystals interfere with one another, is usually idiomorphic. The mineral is colourless in thin slices, and shows either traces of the pinacoidal cleavage or a network of fissures. It often has schiller-inclusions of the nature of minute negative crystals enclosing dendritic growths of magnetite (fig. 29, *A*). Between crossed nicols it sometimes shows a lamellar twinning, with only a slight difference in extinction-position between the alternating lamellæ. Alteration along cracks gives rise to strings of magnetite granules, and complete destruction produces pseudomorphs of greenish or yellow serpentine, or sometimes colourless fibrous tremolite, *etc.*

Of the other ferro-magnesian silicates the commonest in typical peridotites is a rhombic pyroxene; either colourless or pale yellow (*enstatite*) or with faint green and rose pleochroism (*bronzite*): varieties rich in iron do not often occur. The crystals often tend to be idiomorphic. Marked schiller-structures are not very common. Decomposition produces pseudomorphs of bastite. The *augite* is either light brown to colourless, with a high extinction-angle (about 40°) as in many gabbros, or it may show a faint green tint (chrome-diopside). A conversion to brown hornblende is common, and so also are parallel growths of augite and brown hornblende, the former being the kernel. In the more alkaline rocks the augite has a purplish tint with distinct pleochroism, and sometimes shows the 'hour-glass' structure (*cf.* fig. 67, below).

[1] See Farrington, *Journ. Geol.* (1901) ix, 51–66, 174–190, 393–408, 522–532; Fletcher, *Introduction to the Study of Meteorites* (Brit. Museum, 1888)

The amphibole mineral is a common *hornblende* with an extinction-angle of about 20° and colour varying from deep brown to colourless. The pale variety seems due to bleaching, often accompanied by a discharge of magnetite-dust. The *biotite* of peridotites is also frequently of a pale tint.

The felspar of the peridotites proper is either *anorthite* or a bytownite approaching anorthite. That of the picrites is often of a sodic variety, and it is sometimes accompanied by *analcime*, which may in part replace the felspar.

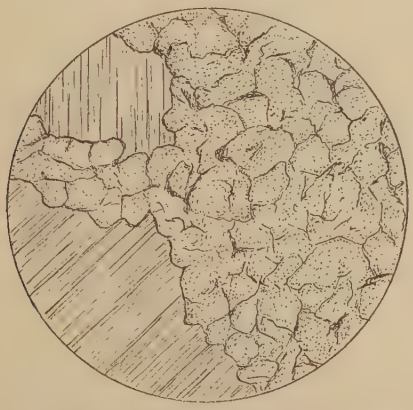

FIG. 26. ENSTATITE-PERIDOTITE WITH PSEUDO-PORPHYRITIC STRUCTURE, SKUTVIK, NEAR TROMSÖ, NORWAY; ×20.

Here olivine is largely in excess, forming a granular aggregate in which are embedded large irregular crystals of a yellowish partly altered enstatite.

Some peridotites have little octahedra of *magnetite*, but some other spinellid mineral is more characteristic. It may be *chromite* (deep brown or opaque), *picotite* (coffee-brown), or *pleonaste* (green). These minerals usually build irregular rounded grains. In some of the rocks *perovskite* is a characteristic mineral, in minute crystals, with very high refractive index. When garnet occurs, it is the magnesian *pyrope*, red in slices.

Structure. The varieties of micro-structure in the peridotites depend largely upon the relative proportions of the constituent minerals. When olivine greatly preponderates, the mutual interference of the several crystals gives rise to a simple granular structure. When crystals of pyroxene are scattered through a matrix of this kind, they are often large and conspicuous, but their outlines show that they are of later crystallization than the olivine. The resulting type of structure has

FIG. 27. PŒCILITIC STRUCTURE IN HORNBLENDE-PERIDOTITE, MYNYDD PENARFYNNYDD, CAERNARVONSHIRE; ×20.

The large plate enclosing olivine-grains and filling the field is a single crystal of hornblende. It is mostly colourless, but becomes deep brown in capriciously arranged patches round the edge.

been termed *pseudo-porphyritic* (fig. 26). If, on the contrary, the pyroxene or hornblende is in excess of the olivine, numerous grains of the latter mineral may be enclosed in each large crystal of the former, giving the type of structure known as *pœcilitic*[1] (fig. 27). Felspar, when present in small amount, occurs always interstitially, but in those allivalites which are

[1] This is quite analogous to the ophitic structure of dolerites (p. 126). See G. H. Williams, *A. J. S.* (1886) xxxi, 30–31; *Journ. of Geol.* (1893) i, 176.

very rich in anorthite this mineral is idiomorphic towards the olivine (fig. 29, *B*).

Corona-structures, whether primary or secondary, are seen in the garnet-bearing peridotites, each crystal of pyrope being surrounded by a broad border or shell known as *celyphite* (Ger. Kelyphit) with radial fibrous structure. The name is not applied to any particular mineral, and the so-called celyphite is not always of the same constitution. A pale or colourless augite is common, while brown hornblende and enstatite are sometimes found, and brown picotite frequently accompanies the pyroxene. Again, brown biotite and magnetite have been observed[1].

A primary gneissic banding, marked by different relative proportions of the minerals in different bands, is very common in peridotites and allivalites; and with it there may go a marked parallel arrangement of crystals. A special feature is the occurrence of narrow bands very rich in chromite or picotite[2] (fig. 29, *C*).

Leading types. The original locality of *dunite* is Mount Dun in New Zealand, but equally fine examples are found among the Tertiary plutonic rocks of Skye and Rum (*op. cit. supra*). In addition to fresh olivine they contain only a spinellid mineral, which is in different varieties opaque chromite, deep brown picotite, or green pleonaste, the first two often in good octahedra. Usually in small relative amount, the spinellid mineral may become very abundant in certain bands of the rock, until it outweighs the olivine (fig. 29, *C*).

Of *enstatite-peridotites* the pseudo-porphyritic type occurs in the South Island of New Zealand[3] and elsewhere; and serpentinized representatives are found in the Lizard district and other British localities. Rocks composed of about equal

[1] Diller, *A. J. S.* (1886) xxxii, 123; *Bull. No.* 38 *U. S. Geol. Sur.* (1887) 15–17.

[2] *Tertiary Igneous Rocks of Skye* (*Mem. Geol. Sur.* 1904) 75–76; *Geology of the Small Isles* (1908) 84–85 (Rum).

[3] Ulrich, *Q. J. G. S.* (1890) xlvi, 625–629, pl. xxiv (Red Hill and Olivine Ranges). This rock is interesting as carrying grains of an iron-nickel alloy (awaruite).

proportions of olivine and rhombic pyroxene occur, with other ultrabasic types, in the Assynt district of Sutherland (fig. 28). By the coming in of a basic felspar we have transitions to norite. Pœcilitic enstatite-peridotites (Harzburg type) are found in a more or less serpentinized state near Belhelvie in Aberdeenshire[1] and elsewhere.

In other specimens from the locality last named diallage takes the place of enstatite, or again the two minerals occur

FIG. 28. ENSTATITE-PERIDOTITE, ASSYNT LODGE, SUTHERLAND; ×20.

A granular aggregate of olivine (*o*), largely serpentinized, and a slightly pleochroic enstatite or bronzite (*e*). These two minerals are in about equal quantity; in addition there are little irregular grains of isotropic green pleonaste (*pl*).

together. There are other British peridotites in which rhombic and monoclinic pyroxenes are both well represented, together with abundant olivine, and some of these resemble the Lherz type from the Pyrenees[2]. Picotite or pleonaste is often present in allotriomorphic grains. This type is non-felspathic. An *augite-peridotite* with at most subordinate enstatite is also

[1] Bonney, *G. M.* 1885, 440–441.

[2] *Ibid.* 1877, 59–64; Teall, *Brit. Petr.* (1888) pl. I, fig. 1.

found. In the Garabal complex, near Loch Lomond[1] the augite is a colourless diallage, and the rock varies from a peridotite rich in olivine to a pyroxenite with only scattered grains of that mineral. In other parts it contains some enstatite, biotite, derivative brown hornblende, and locally bytownite. The augite-peridotites of the Cuillin Hills, Skye[2], commonly consist of olivine to the extent of half to two-thirds, the other chief minerals being a brown augite, often diallagic, and anorthite. Similar rocks occur in Rum[3], where, however, enstatite is more frequent as an additional constituent.

The best-marked type of *hornblende-peridotite* (Schriesheim type) has large crystals of brown hornblende, crowded with grains of olivine and sometimes enclosing also idiomorphic crystals of colourless augite. Such rocks, with a varying proportion of olivine, and with the hornblende often bleached, are found in the Skiddaw district, in Anglesey[4] and Caernarvonshire[5] (fig. 27), and in Co. Wicklow[6]. By the coming in of felspar and diminution of olivine they pass into diorites.

No British *mica-peridotite* has been recorded, but in a rock from the border of Caithness and Sutherland a yellow mica is associated with pale green to colourless hornblende, probably derivative after augite, both minerals enclosing pœcilitically serpentinized grains of olivine (Loch Scye type[7]). A good example from Elliott Co., Kentucky[8], consists of serpentinized olivine and pœcilitic mica, pale yellow-brown to colourless, with perovskite, *etc.*

Of *garnet-peridotites* that from Elliott County, Kentucky[9], is a good example. The pyrope crystals are surrounded by a 'celyphite' border of brown mica with an outer ring of

[1] Wyllie and Scott, *G. M.* 1913, 500–501.
[2] *Tertiary Igneous Rocks of Skye* (*Mem. Geol. Sur.* 1904) 72–73.
[3] Judd, *Q. J. G. S.* (1885) xli, 389–395.
[4] Teall, *Brit. Petr.* pl. iv, fig. 1.
[5] *Ibid.* pl. vii, fig. 5.
[6] Thomson, *Q. J. G. S.* (1908) lxiv, 477–481, 493.
[7] Judd, *Q. J. G. S.* (1885) xli, 401–407; see also Teall, pl. v, fig. 2.
[8] Diller, *A. J. S.* (1892) xliv, 286–289.
[9] Diller, *Bull.* 150 *U. S. G. S.* 290–294, pl. xxxix; *A. J. S.* (1886) xxxii, 121–125; *Bull.* 38 *U. S. Geol. Sur.* (1887).

magnetite-dust, these minerals being supposed to be due to a reaction between the garnet and the olivine.

The *allivalite* type is found in force, in association with various peridotites, in the hills Allival and Askival, in the Isle of Rum[1]. It occurs also, as a local facies, in the Cuillin

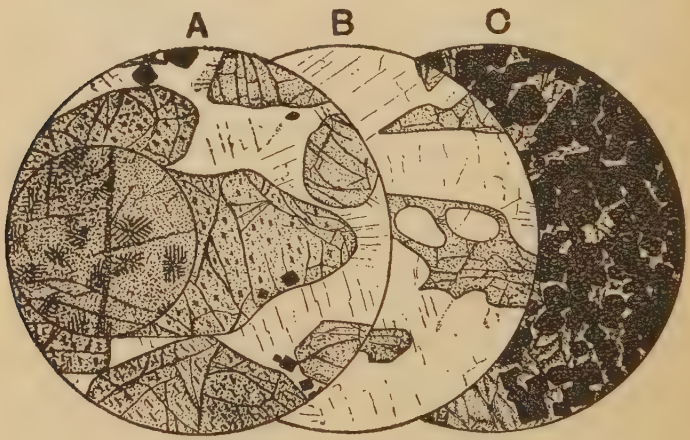

FIG. 29. ULTRABASIC ROCKS, INNER HEBRIDES; ×20.

A. Anorthite-Olivine-rock (Allivalite), Allival, Rum. The abundant fresh olivine contains dendritic inclusions of magnetite, shown on a larger scale in the small inset circle (×100). The opaque octahedra are of chromite.

B. Another variety from the same locality; very rich in felspar, which is here idiomorphic towards the olivine.

C. Dunite, a band very rich in picotite, Loch Scavaig, Skye: composed of deep brown picotite and olivine.

Hills of Skye and near Belhelvie, Aberdeenshire. Excepting a few little octahedra of chromite or chrome-magnetite, olivine and anorthite are the only constituents of the typical allivalite. They are found in all relative proportions in different bands of the complex, which thus presents a series of varieties ranging

[1] *Geology of Small Isles* (*Mem. Geol. Sur. Scot.* 1908) 79–90.

from a pure olivine-rock to a pure anorthite-rock. The mineral which is in excess is idiomorphic towards the other (fig. 29, *A*, *B*). Other varieties arise from the coming in of accessory pyroxene, making connecting links with the eucrites.

Contrasted with these calcic types are those ultrabasic rocks which have affinity with the alkaline series. In peridotites very rich in olivine an alkaline character is shown chiefly by the presence of purplish pleochroic augite, deep brown hornblende probably of a barkevicitic variety, and frequent brown mica, and by the general absence of the rhombic pyroxenes. Examples are found among the Devonian intrusions of Cornwall. One from Polyphant, near Launceston[1], is rich in olivine, partly serpentinized, and contains no recognizable felspar. Another example comes from Menheniot, near Liskeard[2].

Other Cornish rocks of this series (Minver type) have less olivine and more felspar. The only fresh felspar is albite, but the association of this mineral with zoisite, epidote, and calcite suggests that it has replaced a lime-bearing felspar now destroyed. Examples occur at St Minver, near Padstow[3] and again near Polyphant.

More typical *picrites*, in the proper sense, are found among the Carboniferous intrusions of Scotland. They are constantly associated with teschenites (p. 82), and include all gradations between those rocks and extreme melanocratic peridotites. The latter are represented, together with other varieties, in the large composite sill of Lugar, in Ayrshire[4], the rock consisting essentially of olivine (nearly two-thirds of the mass), titaniferous purplish augite, and brown barkevicite hornblende. In the ordinary picrites olivine is less preponderant (though often amounting to one-half), and labradorite and analcime enter in various proportions. In a well-known example from Inch-

[1] Dewey, *Geology of Tavistock and Launceston* (*Mem. Geol. Sur.* 1911) 63–65.

[2] *Geology of Plymouth and Liskeard* (1907) 101; Teall, *Brit. Petr.* (1888) pl. II, fig. 2.

[3] *Geology of Padstow and Camelford* (1910) 43–46; Dewey and Flett, *G. M.* 1911, 207.

[4] Tyrrell, *Q. J. G. S.* (1917) lxxii, 111–113.

colm, near Edinburgh[1], the purple pleochroic augite shows the hour-glass structure, and is bordered by deep brown hornblende. Biotite and ilmenite are other constituents, with a variable amount of felspar, mostly decomposed.

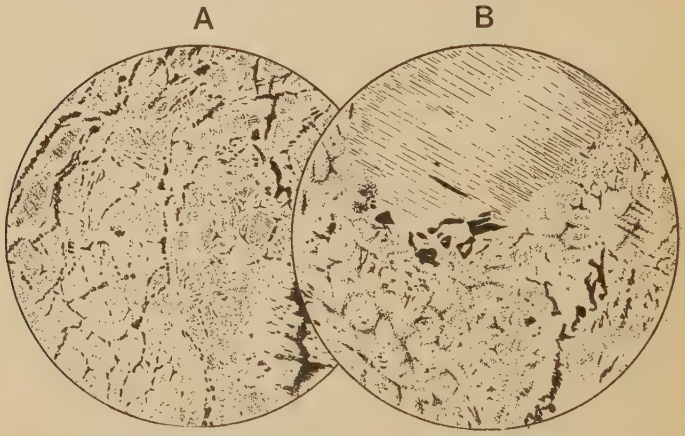

FIG. 30. SERPENTINE-ROCKS, LIZARD, CORNWALL; ×20.

A. Cadgwith: a serpentinized dunite, showing the 'mesh-structure' due to derivation from olivine, with much secondary magnetite.

B. Balk Quarry: this has been an enstatite-peridotite with pseudo-porphyritic structure (*cf.* fig. 26), and the large enstatite crystals are represented by pseudomorphs in bastite, the general matrix showing mesh-structure.

Serpentine-rocks. Hitherto we have noticed only very briefly the secondary changes that affect the minerals of crystalline rocks. In the present family, however, the decomposition of a rock is often so complete that its original nature is detected only by careful study, and the altered rock-masses are commonly denoted by a special name, serpentine-rocks or simply 'serpentines,' expressing their dominant mineral composition. The mineral serpentine is the commonest decomposi-

[1] Teall, *Brit. Petr.* pl. IV, fig. 2, and pl. VII, figs. 1–4; Judd, *Q. J. G. S.* (1885) xli, 400.

tion-product of the non-aluminous magnesian silicates (olivine, the rhombic pyroxenes, and some of the augites and hornblendes), and the purest serpentine-rocks result from the alteration of peridotites[1]. Other decomposition-products occur in the rocks, *viz.* iron-oxides (magnetite and limonite), steatite, carbonates (dolomite, *etc.*), chlorite, and tremolite; but the bulk is serpentine of various kinds, in which may be found undestroyed relics of the original minerals of the peridotite (olivine, diopside, pyrope, chromite, *etc.*).

Of the mineral serpentine some kinds are crystalline and doubly refracting, with interference-colours like quartz or felspar, and show faint pleochroism when the green tint is sufficiently pronounced. The habit is fibrous (chrysotile) or scaly (antigorite, *etc.*). Other kinds are amorphous and sensibly isotropic. Much of the serpentine occurs in definite pseudomorphs, and often retains something of the structure of the parent mineral to indicate its source. We may distinguish four cases:

(i) Serpentine derived from olivine, with the '*mesh-structure*' (Tschermak's 'Maschenstructur'; see p. 74 and fig. 30).

(ii) Serpentine derived from enstatite or bronzite, in distinct pseudomorphs with the *bastite-structure* (see p. 73 and fig. 30, *B*).

(iii) Serpentine derived from a non-aluminous hornblende, with '*lattice-structure*' ('Gitterstructur' of Weigand). Here the cleavage of the hornblende is marked by veins of birefringent serpentine in two sets making the characteristic angle $55\frac{1}{2}°$. This serpentine is minutely fibrous, with the fibres set perpendicularly to the cleavage of the hornblende. The rest of the pseudomorph is of serpentine giving no definite crystalline reaction and consisting probably of a confusedly fibrous aggregate.

(iv) Serpentine derived from a non-aluminous augite, with '*knitted-structure*' ('gestrickte Structur' of Hussak). This con-

[1] For descriptions and coloured figures of numerous serpentine-rocks see Wadsworth, *Lithological Studies* (1884). For a general sketch of observations and opinions on serpentine see Teall, *Brit. Petr.* chap. vi.

sists chiefly of serpentine with scaly habit (antigorite). The scales give straight extinction and low polarization-tints. They occur in two closely interlacing sets parallel to the cleavage-planes of the augite, and so making an angle of about 87° with one another. The interpretation of the structure, however, is doubtful, and it appears that serpentine derived from olivine may show the same characters[1].

The source of serpentine in rocks can often be made out by these various characters, and it is placed beyond doubt when any unaltered relics of the parent mineral remain. In addition there may be serpentine encroaching upon contiguous minerals or traversing them in veins: this is, as a rule, sensibly isotropic.

The best-known *serpentine-rocks* in this country are those of the Lizard district in Cornwall[2]. On the border of the mass the rock has been a dunite, and shows merely the mesh-structure (fig. 30, *A*). The only primary mineral which is always unchanged is the spinellid, usually in small amount but richly present in certain bands ('chromite-serpentine'). The interior of the mass is of *bastite-serpentine*, and has been an enstatite-peridotite of the pseudo-porphyritic type (fig. 30, *B*). Another variety of serpentine-rock is characterized by the occurrence of slender prisms of colourless secondary tremolite, and often contains a little felspar, usually decomposed.

Various serpentinous rocks are found near Holyhead and in neighbouring parts of Anglesey. In rocks at Four-mile Bridge much of the serpentine has the knitted structure. In Scotland numerous examples have been described from the Ballantrae district of Ayrshire, various parts of the Highlands, and the Shetland Isles.

[1] Bonney and Raisin, *Q. J. G. S.* (1905) lxi, 690–714, pl. xlv.

[2] Flett, *Geology of Lizard* (*Mem. Geol. Sur.* 1912) 61–64; Teall, *Brit. Petr.* pl. i, fig. 2, and pl. ii, fig. 1.

B. HYPABYSSAL ROCKS

Some petrologists are content to divide the igneous rocks into two great groups, according as their structural characters indicate consolidation under deep-seated or under superficial conditions. Others, however, recognize another group intermediate between these two. Thus Rosenbusch inserts between his 'Tiefengesteine' and 'Ergussgesteine' a group 'Ganggesteine' or 'dyke-rocks.' The rocks to be treated under the present head correspond in a general way, though not precisely, with the last named, but Brögger's name 'hypabyssal' is adopted as more accurately expressing the characters upon which the group is founded.

Although this threefold division seems to be necessitated by a comparative study of the great variety of rock-types met with in nature, it must be admitted that the hypabyssal group is a somewhat artificial one, the rocks included in it lacking any well defined set of common characteristics distinguishing them from the other two groups. Any definition would have to be framed chiefly in negative terms, and would bring together types presenting many points of difference from one another. Most of them are holocrystalline, but in some a glassy residue is found. In some families the porphyritic structure is characteristic[1], as it is in the volcanic rocks; in others it is wanting or non-significant: but even the holocrystalline non-porphyritic types have structural and mineralogical characters, to be noted below, which differentiate them from rocks of truly deep-seated origin. By relatively rapid cooling, however, the margin of a plutonic mass may assume the characters of a hypabyssal rock (fig. 32).

[1] On the significance of this structure see Cross, *14th Ann. Rep. U. S. Geol. Sur.* (1895) 232–235; Pirsson, *A. J. S.* (1899) vii, 271–280; Crosby, *Amer. Geol.* (1900) xxv, 299.

CHAPTER VIII

ACID HYPABYSSAL ROCKS

The acid hypabyssal rocks embrace a considerable range of varieties, bridging over the difference between the even-grained, holocrystalline granites and the porphyritic, largely glassy rhyolites. The porphyritic character is almost universal, but the ground-mass which encloses the phenocrysts may be holocrystalline, partly crystalline and partly glassy, or wholly glassy. On the nature and special structures of the ground-mass depend chiefly the several types usually recognized among these rocks. All agree in that the constituent minerals include in the first rank felspars rich in alkali and usually quartz, while ferro-magnesian minerals and free iron-ores occur only in relatively small quantity, and are sometimes wanting.

On examination of their mineral constitution and characteristic structures, the more crystalline types are readily referred to their proper positions; but, in proportion as the bulk of the rock comes to consist of unindividualised glassy matter or an irresolvable cryptocrystalline 'base,' the criteria become fewer. In particular, the first stage of consolidation (that of the phenocrysts) may have been arrested before quartz (the last mineral) began to crystallize, and so, if the ground-mass consolidates as a glass, we may have a thoroughly acid rock without quartz. Thus the most glassy rocks (pitchstones) belonging to this family are not always to be distinguished by the microscope alone from less acid pitchstones. Again, they are scarcely divided from some glassy rhyolites (obsidians).

The nomenclature of these acid rocks is confused. The name 'felsite' or—if containing evident phenocrysts of quartz—'quartz-felsite' has been applied in this country not only to these rocks but also to many volcanic rocks (acid and intermediate), and its usage lacks precision and significance. The name quartz-porphyry, borrowed from the German, covers most of the rocks, but not all, since porphyritic quartz may be

wanting: this term is also used by Continental writers for the 'older' acid lavas. For a type rich in soda, and having some mineralogical peculiarities, the name quartz-ceratophyre (Ger. Quarzkeratophyr) has been used. It will be convenient to speak of the family, as a whole, as the acid intrusives. The names applied to particular types will be noticed in connection with the ground-mass.

Constituent minerals. We notice here especially the minerals occurring as phenocrysts. Of these, the felspars include *orthoclase* (not microcline) and an acid plagioclase such as *oligoclase*. The two are commonly associated, and both build idiomorphic crystals with the usual types of twinning. A narrow zone of orthoclase surrounding each plagioclase crystal is seen in some rocks. The characteristic felspar of the quartz-ceratophyres is *anorthoclase*.

The *quartz* has crystallized in the ordinary hexagonal pyramids, sometimes with narrow prism-faces, but the crystals are frequently rounded and eaten into, owing to corrosion by the magma, and may have lost all crystal-outlines. In the rock-types most nearly approaching granites (granite-porphyries) the quartz contains fluid-pores: in other types the inclusions are mostly of glass or portions of the ground-mass (fig. 31, *A*). As already mentioned, quartz-phenocrysts are not always present.

The brown *biotite*, which occurs in many of the rocks, has the same characters as in granites, and carries the same inclusions. It is usually idiomorphic. The most common mode of alteration is chloritization. Hexagonal flakes of *muscovite* are found in a few of the granite-porphyries only.

A green *hornblende* in well-built crystals is a rather exceptional constituent. The deep blue soda-bearing amphibole *riebeckite* occurs in a few rocks, always in very ragged allotriomorphic crystals (fig. 31, *B*). The *augite* of these rocks is a pale greenish variety like that in some granites, but occurs here much more frequently. It builds idiomorphic crystals in many granophyres and pitchstones. A few rocks rich in soda contain *ægirine*. A rhombic pyroxene (*bronzite*) is also known.

As accessories, *apatite* and *zircon* are widely but sparingly distributed, while the iron-ores are usually represented only by a little *magnetite*. Such minerals as garnet, allanite, and pinite pseudomorphs after cordierite occur in special localities. Some granite-porphyries carry *tourmaline* (Cornwall).

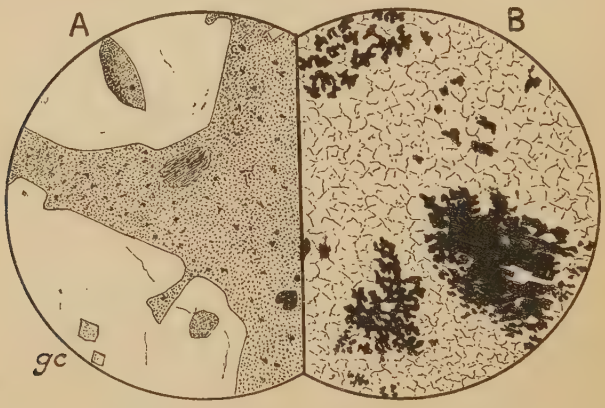

Fig. 31; × 20.

A. Quartz-Porphyry, dyke, King's Cave, Arran. The quartz-phenocrysts are partly corroded, and contain inclusions of the ground-mass, as well as relatively large glass-cavities (*gc*) with the form of 'negative crystals.'

B. Riebeckite-Microgranite ('Paisanite'), Mynydd Mawr, Caernarvonshire. The nearly opaque crystals of sponge-like form are the dark blue soda-amphibole, riebeckite.

Ground-mass and structures. The types which approach most nearly to the plutonic habit are known as *granite-porphyry*. Here relatively large idiomorphic crystals of quartz and felspars, with mica or some other ferro-magnesian mineral, are enclosed in a fine-textured crystalline ground-mass of felspar and quartz. The structure of this ground may resemble that of a granite, or may be distinguished by a more marked idiomorphism of the lath-shaped felspars, usually untwinned. Mica may also occur in a second generation as part of the ground-

mass. A granite-porphyry is not infrequently found as a marginal modification of a granite (fig. 32, *A*). If porphyritic crystals are scarce or wanting, the term *microgranite* is employed.

Very common are those *quartz-porphyries* in which the phenocrysts, consisting of felspars, more or less corroded quartz, and biotite or some other constituent, are embedded in a very finely crystalline ground-mass of felspar and quartz with no special peculiarity of structure.

When the texture of the ground-mass sinks to such minuteness as to be not clearly resolved under the microscope, it may be described as *cryptocrystalline* ('microfelsitic' of some authors). For such rocks Rosenbusch used the term felsophyre[1]. Without entering into a discussion of an obscure subject, it may be said that this cryptocrystalline ground is probably in some cases original, in other cases due to secondary change (devitrification) of a ground-mass originally glassy.

The glassy (or 'vitrophyric') type of ground-mass is seen in the rocks known as *pitchstones*. In some of these, phenocrysts of felspar, *etc.*, are only sparingly present, the great bulk of the rock consisting essentially of isotropic glass. This glassy ground, however, includes in many cases innumerable minute and imperfectly developed crystalline growths (*crystallites*) with regular grouping (fig. 37). These minute bodies will be more fully noticed in connection with the acid lavas. The pitchstones frequently show perlitic cracks, and occasionally some of the flow-phenomena which are better exhibited in lavas. Typical pitchstones, excluding lava-flows, are of quite limited distribution.

In the above types we have what may be regarded as a graduated transition from the granitic to the rhyolitic structures, the only gap, that between cryptocrystalline matter and glass, being one which the instruments at our disposal do not enable us to bridge. There is, however, a second, more or less distinct, line of transition, parallel to the former but characterized by a different set of structures, *viz.* micrographic intergrowths of felspar and quartz and regular radiate aggregates

[1] *Cf.* Teall, *G. M.* 1885, 108–111.

of felspar fibres. To these structures Rosenbusch applied the somewhat inappropriate term 'granophyric,' including both micropegmatitic and microspherulitic; and the rocks having a ground-mass of this nature are very generally known as *granophyres*.

We have already noticed in some granites a micrographic intergrowth of the kind named micropegmatite; but when the whole mass of the rock, exclusive of crystals of certain

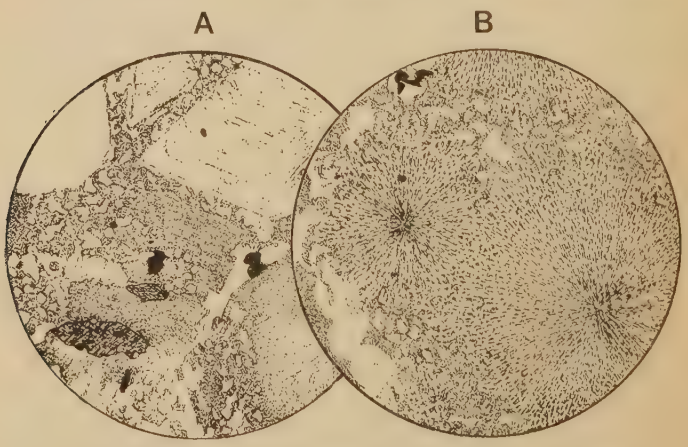

FIG. 32. MARGINAL MODIFICATIONS OF GRANITE, SKYE; ×20.

A. Hornblende-Granite-Porphyry, Camas Malaig, Loch Slapin. The orthoclase is clouded; oligoclase and quartz clear.

B. Spherulitic Granophyre, Glas-bheinn Bheag.

minerals, takes on this character, we have a type characteristic of hypabyssal rather than abyssal rocks as here understood. In such rocks the quartz and the greater part of the felspar form a micrographic ground-mass, which may enclose idiomorphic crystals of some ferro-magnesian mineral (augite or biotite) or of felspar (mostly plagioclase). Further, the micrographic intergrowth may come in to some extent in rocks which on the whole would be placed with the granite-porphyries

or the microgranitic type. When the intergrowth is on a relatively coarse scale, it is often rude and irregular, but the finer-textured '*micropegmatite*' shows great regularity and often a definite arrangement (fig. 33, *B*). In particular it frequently forms a regular frame surrounding phenocrysts of felspar, and it can often be verified that the felspar of the intergrowth is in crystalline continuity with the felspar crystal which served as a nucleus. The appearance is as if the original crystal had continued to grow throughout the final consolidation of the rock, enclosing the residual excess of silica as intergrown quartz. Sometimes a line of Carlsbad-twinning can be traced from the crystal through the surrounding frame. There is no doubt that plagioclase felspar, as well as orthoclase, enters into such micrographic intergrowths. Less frequently the quartz of the intergrowth is seen to be in crystalline continuity with a quartz crystal or grain, upon which it has grown.

The finest micrographic intergrowth tends especially to a stellate or radiate ('centric') arrangement, with or without a nucleus of an earlier crystal. As the growth becomes very delicate in texture, the sectors within which the felspar extinguishes simultaneously become narrower, and are represented between crossed nicols by dark rays when their direction makes a small angle with one of the cross-wires. When the structure is on too minute a scale to be resolved by the microscope, it may be termed, by analogy, cryptographic. The optical characters of such an aggregate appear to be determined by the minute radially arranged fibres of felspar, which obscure the quartz. The structures known as *microspherulitic* and pseudo-spherulitic in acid rocks are probably of this nature (fig. 32, *B*). Between crossed nicols they show characteristically a black cross, caused by extinction in those fibres which lie nearly parallel to one of the cross-wires (fig. 35). Such growths cluster round porphyritic crystals of quartz or felspar, or, as innumerable closely packed minute spherules, constitute almost the whole of the ground-mass (fig. 36, *B*). Isolated spherulites or bands of spherulites may occur in a microcrystalline or vitreous or devitrified ground.

Leading types. We proceed to select a few examples illustrating the several points indicated above. In view of the

frequent association of the different types of ground-mass in one district, or even in parts of one intrusion, we shall not find it convenient to follow any strict order.

The varied group of Ordovician intrusive rocks in Caernarvonshire[1] include some *granite-porphyries* of a well-marked type. Quartz is wanting among the phenocrysts, which are chiefly of oligoclase. One example at the head of Nant Ffrancon has a ground-mass of allotriomorphic quartz and felspar (chiefly orthoclase). The ferro-magnesian constituent is biotite. Others, quarried at Yr Eifl and near Nevin, have a ground-mass of idiomorphic felspars and interstitial quartz. These contain augite, usually without biotite. Other rocks in the district, all augitic, show more or less tendency to micrographic structures, and some are typical *granophyres*. Beautiful examples occur in the hills above Aber and at Moel Perfedd in Nant Ffrancon. The growth of the micropegmatite round felspar crystals is well exhibited, and in some cases a narrow zone of orthoclase is seen interposed between a plagioclase crystal and the surrounding growth. The structure is rarely so minute as to approximate to the spherulitic. Many of the smaller intrusions in the district, *e.g.* near Clynog-fawr, are of quartz-porphyry with a cryptocrystalline ground, which may possibly be due to devitrification. Porphyritic quartz, which is wanting in the more evidently crystalline types, appears here in corroded crystal-grains.

The 'elvan' dykes of Cornwall and Devon[2] include granite-porphyries and especially *quartz-porphyries* with microcrystalline ground-mass. The phenocrysts are large felspars, pyramidal or rounded quartz crystals, and often two micas. The quartz contains either glass-inclusions or fluid-pores, sometimes in the form of negative crystals, which may enclose a salt-cube as well as a bubble. Tourmaline is of frequent occurrence in crystals or stellate groups of needles, and is sometimes seen to replace felspar. The porphyritic felspars are usually turbid from incipient alteration, and the ground-mass is very often crowded with minute flakes of secondary white mica.

[1] *Bala Volc. Ser. Caern.* (1889) 48–56.
[2] See *Memoirs* of Geological Survey.

The Lake District contains examples of *microgranites*, such as the rock quarried at Threlkeld. Granophyres also occur, the large Buttermere and Ennerdale intrusion being of a *micropegmatitic* rock with either biotite or augite, resembling some Caernarvonshire examples[1]. The dykes of Armboth and Helvellyn have a spherulitic ground mass enclosing idiomorphic crystals of quartz and felspar. The spherulitic growth, which

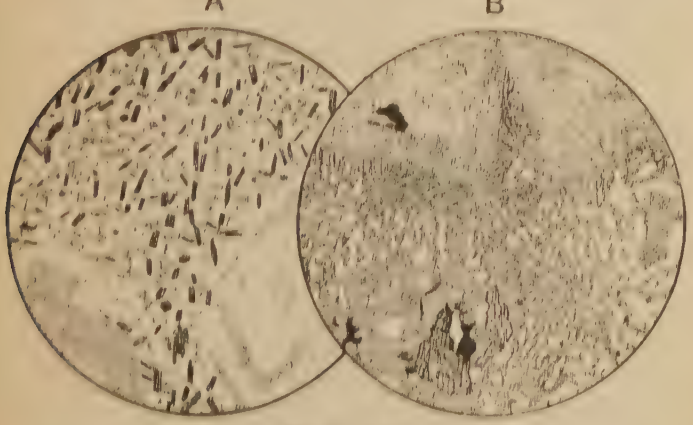

FIG. 33; ×20.

A. Æginne Felsite, approaching the grorudite type, Inchmadamph, Assynt, Sutherland: showing abundant little crystals of æginine scattered through the microcrystalline ground-mass.

B. Augite-Granophyre, Meall Dearg, Glen Sligachan, Skye.

does not always give a good black cross, is clustered especially about the quartz crystals. A few garnets are present. Near Dutton Pike, in Edenside[2], occurs a granite porphyry with both muscovite and biotite. The two micas occur both as phenocrysts and in the ground mass. The other phenocrysts are idiomorphic quartz and felspar, chiefly plagioclase but with a few large orthoclase crystals. The granophyre of Carrock

[1] Rastall, *Q. J. G. S.* (1906) lxii, 268–269, 270, pl. xxviii.

[2] *Q. J. G. S.* (1891) xlvii, 549.

Fell[1] contains a pale augite in good crystals, often uralitized or otherwise altered, and rarely a little biotite. There are also idiomorphic felspars, usually oligoclase, and some granules of iron-ore. The ground-mass shows in different specimens, or even in one slide, every gradation, from a coarse irregular micropegmatite through exquisitely regular micrographic and cryptographic structures to what would be described as

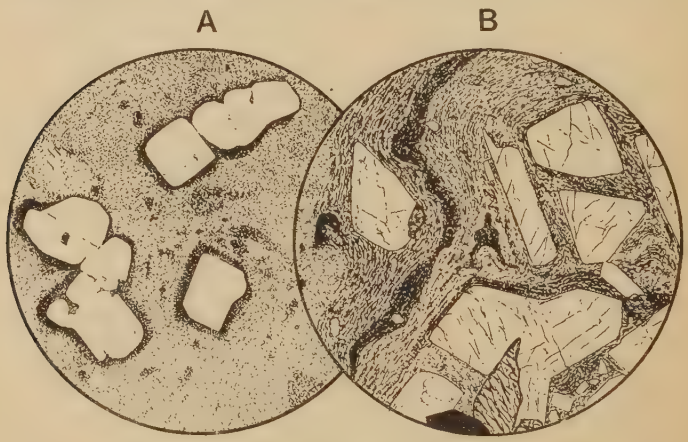

Fig. 34. Scottish Quartz-Porphyries; ×20.

A. Kilchoan, Ardnamurchan. Phenocrysts of quartz only; ground-mass fine-textured, probably devitrified.

B. Beinn nan Stac, Rum. Phenocrysts of felspar, augite, and magnetite; ground-mass showing different types of structure, with strong flow-banding.

spherulitic. These intergrowths usually make up the whole ground-mass, though sometimes part of the quartz forms irregular grains. The arrangement is sometimes 'centric,' but more usually peripheral to the felspar phenocrysts, forming a regular border to them. It can often be seen that the felspar of the intergrowth is continuous with that of the crystal, and much of it must be plagioclase.

[1] *Q. J. G. S.* (1895) li, 126–130.

The biotite-bearing *quartz-porphyries* of the Cheviots[1] have sometimes granophyric structures, but are more commonly micro- to cryptocrystalline. Frequently the ground-mass encloses patches of micropegmatite like porphyritic crystals, sometimes showing the outlines of idiomorphic felspar. This feature is also well shown in a microgranitic quartz-porphyry

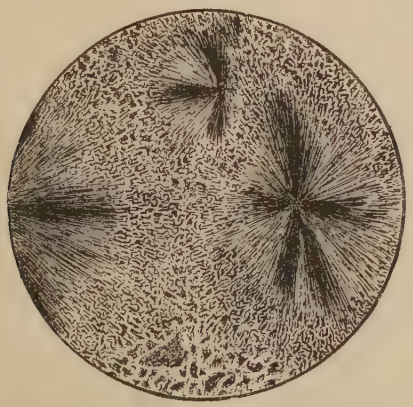

FIG. 35. SPHERULITIC GRANOPHYRE, GLAS-BHEINN BHEAG, SKYE; ×20, CROSSED NICOLS.

The spherulites (pseudo-spherulites of some authors) consist of a cryptographic intergrowth of felspar and quartz arranged radially about centres. At the periphery of each spherulite the cryptographic passes into a visibly micrographic structure, and the radial arrangement becomes less marked. Between the spherulites are interspaces in which the structure is granular.

from the Black Hill in the Pentlands[2]. Among Scottish quartz-porphyries of Tertiary age those which form numerous sills and dykes in the Isle of Arran[3] are worthy of notice. The ground-mass is microcrystalline in the larger intrusive bodies but often cryptocrystalline in the smaller (fig. 31, *A*). Other

[1] Teall, *G. M.* 1885, 111; Kynaston, *Tr. Edin. G. S.* (1899) vii, 402–408, pl. xxv, figs. 2, 3; Teall, *Brit. Petr.* pl. xxxi, fig. 2.

[2] Flett, *Tr. Edin. G. S.* (1899) vii, 483–486, pl. xxvii, figs. 2–4.

[3] *Geol. N. Arran* (*Mem. Geol. Sur. Scot.* 1903) 109–110.

quartz-porphyries are found in Skye, Rum (fig. 34, *B*), Mull, and Ardnamurchan (fig. 34, *A*). The ferro-magnesian minerals, always in subordinate amount, are biotite and more frequently augite.

The British Tertiary intrusions furnish also many examples of *granophyres*. The large granite masses of Skye, Mull, *etc.* often pass into micrographic modifications, and sometimes at the margin into cryptographic[1] (fig. 32, *B*); but the same types,

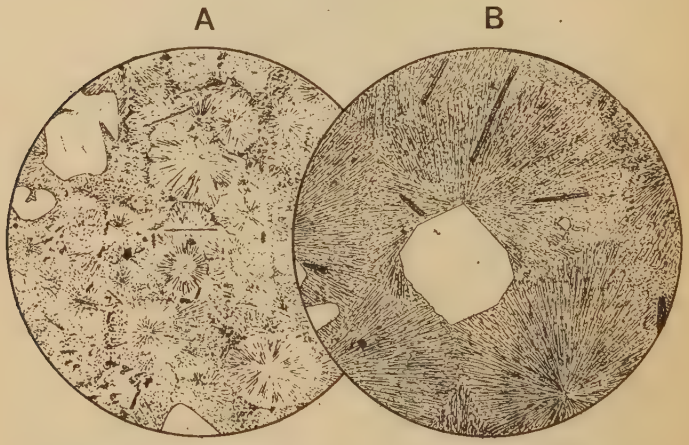

FIG. 36. SPHERULITIC GRANOPHYRES, SCOTLAND; ×20.

A. Dyke on Beinn Nuis, Arran. *B*. Sill at Broadford, Skye.

with great variety of structure in detail, are found in many dykes and sheets. Here too the ferro-magnesian element, only sparingly present, is usually augite; but in some cases it is hornblende or biotite, as in examples from near Newcastle and Hilltown, Co. Down[2]. The *spherulitic granophyres* are of the cryptographic kind, giving a more or less distinct black cross between crossed nicols (fig. 35). Sometimes spherulites occur

[1] *Tert. Ign. Rocks Skye* (*Mem. Geol. Sur.* 1904) 283–286.
[2] Hyland, *Sci. Proc. Roy. Dubl. Soc.* (1890) vi, 420–430.

isolated in a ground-mass otherwise of simple microcrystalline structure: more frequently they make up the chief part or the whole of the ground-mass (fig. 36).

Of special interest are the well-known Arran *pitchstones*[1], of which some are of acid, others of subacid composition. They form dykes and sheets of Tertiary age. The phenocrysts are of orthoclase, quartz, plagioclase, and augite, varying in different examples and sometimes occurring very sparingly. The ground-mass is of glass crowded with crystallites, which often assume peculiar groupings. In one variety needle-shaped microlites (belonites) of hornblende occur, each forming the trunk of a delicate arborescent aggregate of more minute bodies (Corriegills, fig. 37, *A* and *B*). In another variety occur crosses, each of the four arms carrying a plume-like growth (Tormore, fig. 37, *C*). Again, little rod-like bodies frequently occur as a fringe arranged perpendicularly on the faces of phenocrysts. The general mass of the glass is full of very minute crystallitic bodies, but round each grouping is a clear space, indicating that the tree-like or other growth has been built up at the expense of the surrounding part. Flow-structures are only occasionally met with, and perlitic cracks are not common. Dykes of pitchstone with various crystallitic growths occur also in Skye (Glamaig near Sligachan and Coirechatachan near Broadford)[2], on the south coast of Eigg, and in Donegal (Barnesmore Gap)[3]. All these British pitchstones are remarkable for their richness in ferro-magnesian crystallites, sometimes of hornblende, sometimes of augite. Some of the Arran pitchstones are of intermediate rather than acid composition. In some of the Eigg dykes, and in the sheet of porphyritic pitchstone which makes the Sgùrr in the same island[4], on the other hand, the abundant crystallites are of felspar. The large felspar crystals are of anorthoclase or

[1] Allport, *G. M.* 1872, 1–9; 1881, 438; Bonney, *G. M.* 1877, 499–511; Judd, *Q. J. G. S.* (1893) xlix. 546–551, 559–561, pl. xix; Teall, *Brit. Petr.* pl. xxxiv, figs. 3, 4; Harker, *Geol. N. Arran*, 120–123; Scott, *Tr. Geol. Soc. Glasgow* (1913) xv, 16–37, pl. xv, xvi.

[2] *Tert. Ign. Rocks Skye* (*Mem. Geol. Sur.* 1904) 403, 407, pl. xx, fig. 5; xxiv, fig. 3.

[3] Sollas, *Sci. Pr. Roy. Dubl. Soc.* (1893) viii, 87–91.

[4] Judd, *Q. J. G. S.* (1890) xlvi, 380; Harker, *Geol. of Small Isles* (*Mem. Geol. Sur. Scot.* 1908) 173–175.

cryptoperthite, and the other porphyritic elements are augite, enstatite, and magnetite. The dykes of Eigg, which belong to the less acid group of pitchstones, afford good illustrations of devitrification.

There remain those acid hypabyssal rocks which are characterized by special richness in alkali, and specifically in

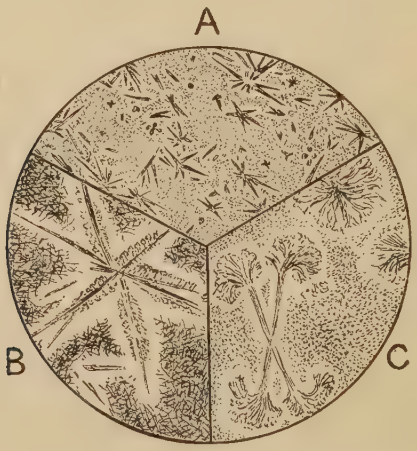

Fig. 37. Pitchstones, Arran.

A Arborescent crystallites with stellate grouping, Corriegills; ×20.
B. The same; ×100.
C. Plumose crystallites with cross-like grouping, Tormore; ×100.

soda. A *soda-granite-porphyry* has been described from Porthallow Cove, near the Lizard[1]. Albite makes up fully half of the rock, occurring as phenocrysts and also with orthoclase and quartz in the ground-mass. In a somewhat more acid example from Tayvallich, in Kintyre[2], the phenocrysts are of microperthite and the ground-mass of albite, orthoclase, and quartz with biotite and muscovite. The *quartz-ceratophyres* are finer-

[1] Flett, *Geology of Lizard* (*Mem. Geol. Sur.* 1912) 186-187.
[2] *Geology of Knapdale, etc.* (*Mem. Geol. Sur. Scot.* 1911) 93–94.

textured rocks. One from near Mevagissey, in Cornwall[1], has phenocrysts of alkali-felspar, and less frequently of quartz, in a felspathic ground-mass with microlitic structure. Secondary mica and carbonates are present as alteration-products. Probably some of the 'soda-felsites' of Leinster[2], of Ordovician age, are to be placed here. They are microcrystalline rocks, with or without porphyritic structure, consisting essentially of predominating felspar and quartz. Plagioclase is much more abundant than orthoclase, and is sometimes albite, sometimes possibly anorthoclase or cryptoperthite.

More remarkable are those rocks in which the ferro-magnesian minerals also are of soda-bearing varieties. From Mynydd Mawr, in Caernarvonshire, comes a rock (fig. 31, *B*) containing ragged riebeckite, with microperthitic felspars and some quartz-grains, in a ground-mass of quartz and felspar with microlites of some unknown mineral[3]. A somewhat similar rock occurs at Ailsa Craig[4], and both are closely allied to rocks from Texas styled paisanite. An ægirine-bearing type found near Inchnadamph in Assynt, Sutherland[5], consists of polysynthetic aggregates representing original phenocrysts of alkali-felspar, streaks of microcrystalline quartz (scarce), and a crypto- or microcrystalline felspathic matrix crowded with acicular microlites of ægirine (fig. 33, *A*). This has very decided resemblance to an interesting type described by Brögger from the Christiania district (Grorud type), which, however, is of somewhat more acid composition, and richer in ægirine.

[1] Teall, *Geology of Mevagissey* (*Mem. Geol. Sur.* 1907) 56.

[2] Hatch, *G. M.* 1889, 70–73, 545–549.

[3] *G. M.* 1888, 225–226, 455–456; *Bala Volc. Ser. Caern.* (1889) 50–52.

[4] Teall, *M. M.* (1891) ix, 219–221; Heddle, *Tr. Edin. G. S.* (1897) vii, 266, pl. xv, fig. 1. Riebeckite occurs also in the granophyre of Meall Dearg, in Skye; Teall, *Q. J. G. S.* (1894) l, 219; Harker, *Tert. Ign. Rocks Skye* (1904) 158–159, 165.

[5] Teall, *G. M.* 1900, 391.

CHAPTER IX

PORPHYRIES AND PORPHYRITES

The rocks which are for convenience grouped together in this chapter belong to various hypabyssal types of intermediate chemical composition. Some have not a very wide distribution, and they graduate on the one hand into the acid types already discussed, on the other into the more peculiar family of the lamprophyres.

The porphyritic structure characterizes almost all the rocks in question, and in most of the types is marked by felspar phenocrysts of relatively large size. The ferro-magnesian minerals are often confined to the elements of the earlier period of crystallization. Original quartz is found in the more acid types only, and is almost always restricted to the ground-mass.

The rocks may be regarded as standing between the plutonic syenites, diorites, *etc.*, on the one hand, and the volcanic trachytes, dacites, and andesites on the other, just as the rocks treated in the preceding chapter stand between the granites and the rhyolites. According as the dominant constituent is an alkali-felspar or a soda-lime-felspar, they fall into two families, to be distinguished as porphyries and porphyrites respectively. To these must be added the types distinguished by the presence of a felspathoid mineral in addition to alkali-felspar. These correspond in a general way with the plutonic nepheline-syenites, and may be considered to constitute a separate family.

Under the first head we may recognize *syenite-porphyry* and *orthoclase-porphyry* (with orthophyre), corresponding with granite-porphyry and quartz-porphyry, among the acid rocks. From these orthoclase-bearing rocks have been separated others characterized by a soda-felspar, under the name *ceratophyre* (Ger. Keratophyr). There are also nepheline-syenite-porphyry and nepheline-porphyry (with *tinguaite*), which are rocks of restricted distribution.

Of the rocks characterized by soda-lime-felspars, the types most nearly approaching the plutonic have been styled *diorite-porphyrite, etc.*, the others being termed simply porphyrites. Since some ferro-magnesian mineral is usually a prominent constituent, we have the divisions *mica-porphyrite, hornblende-porphyrite*, and *augite-porphyrite*. If a little porphyritic quartz be present we have a *quartz-porphyrite* (quartz-mica-porphyrite).

It must be noted that writers who make no distinction in nomenclature between intrusive and volcanic rock-types use some of the above names in a more extended sense. Thus the Continental petrologists include under the term porphyrite the 'older' andesitic lavas, while some British authors apply the same name to andesites modified by secondary changes (partial decomposition, *etc.*).

Constituent minerals. The *orthoclase* phenocrysts of the porphyries are similar to those in the quartz-porphyries. In the porphyrites this mineral does not occur except in the ground-mass. A *plagioclase* felspar accompanies the porphyritic orthoclase in some of the porphyries, and forms the most conspicuous phenocrysts in the porphyrites. Here it builds idiomorphic or rather rounded crystals, with twinning often on two or three different laws. It ranges in the porphyrites from oligoclase to labradorite, and frequently shows strong zoning between crossed nicols. A parallel intergrowth of orthoclase and plagioclase is common in some porphyries. In certain types of that family also occurs a felspar which has been referred to *anorthoclase*, while it has also been explained as a minute parallel intergrowth of a potash- and a soda-lime-felspar. Viewed between crossed nicols, a crystal is often seen to be divided rather irregularly into portions with different optical behaviour, sometimes one part finely striated, another without visible striation. In certain special rocks (rhomb-porphyries) the crystal has a peculiar habit, which gives a lozenge-shaped section; in the ceratophyres it has the usual habit, giving rectangular sections. In some highly sodic types *albite* is the dominant felspar.

As phenocrysts *quartz* is found only sparingly in a few rocks, but it enters into the ground-mass of all the more acid

of the porphyries and porphyrites, though less abundantly than in the true acid rocks.

The most usual ferro-magnesian minerals are brown *biotite* and a pale or colourless idiomorphic *augite*. Some of the porphyrites have *hornblende* in sharply idiomorphic prisms, often twinned: it is more usually brown than green. In rocks rich in alkali the coloured constituent is often ægirine-augite or true *ægirine*, or again deep blue *riebeckite*.

As accessories, *apatite* and *iron-ores* (often titaniferous) may occur in varying quantity, the latter not being abundant. Exceptionally *olivine* and other minerals are present.

In those rocks which contain *nepheline* that mineral occurs in one or two generations. As phenocrysts it is idiomorphic, while the little crystals in the ground-mass may or may not have definite shape. The 'liebenerite' pseudomorphs in certain porphyries have been supposed to represent nepheline. They consist essentially of a pale mica, and may with equal probability come from the destruction of cordierite. Some of these rocks rich in alkali carry melanite *garnet*.

Ground-mass and structures. In the great majority of the rocks here considered the ground-mass is holocrystalline, with a fine texture and with various types of structure. It consists essentially of felspar or, in the more acid members, of felspar and quartz. In the porphyries the felspar is usually in minute prisms, short in comparison with their length, and as a rule untwinned. Quartz, if present, occurs interstitially. The little prisms may have more or less of a parallel arrangement, due to flow. Such short and relatively stout prisms are usually referred to orthoclase: if the crystals have the 'lath'-shape, they are probably of a plagioclastic variety. Any approach to an allotriomorphic character is uncommon, and the micrographic intergrowths so frequent among the acid rocks are not found here. In the nepheline-bearing rocks a more allotriomorphic type of structure is often found; while the bostonites and allied rocks show an approach to the volcanic trachytes, often with marked flow-structure.

The ground-mass of the porphyrites is also in general

holocrystalline, consisting essentially of felspar, or, in the more acid varieties, of felspar and quartz. In this latter case the rocks may reproduce some of the characteristic structures noted in the preceding chapter, such as the cryptocrystalline and the micrographic. Other porphyrites have the 'orthophyric' type of ground-mass (with short felspar prisms), as in the porphyries, but there is every gradation from this to the allotriomorphic. In some of the more basic members the ground-mass consists of little lath-shaped plagioclase prisms with more or less noticeable flow-arrangement, an approach to the character of some andesites (microlitic structure).

Glassy and vitrophyric rocks are not unknown in the families in question. Some of the Arran pitchstones, for example, have the composition of intermediate rather than acid rocks.

Leading types. Those groups characterized by alkali-felspars and by nepheline are only scantily represented in Britain, but porphyrites have a wide distribution.

Syenite-porphyries in considerable variety have been described from the United States. Some with hornblende occur in the Little Belt Mts, Mont.[1] From Cape Ann, Mass., Washington[2] describes dykes of quartz-syenite-porphyry, in which the coloured silicates are green hornblende and subordinate biotite. A rock from Coney Island, Salem, Mass., has abundant phenocrysts of felspar (microperthite and cryptoperthite) in a ground-mass of similar felspars and needles of a greenish blue soda-amphibole (catophorite), with fluxion-structure. Augite-syenite-porphyry has been noted at Lake Chautauqua, N.Y., Albany, N.H. (with accessory bronzite), and other places.

Rocks which belong to the *orthophyre* type (including orthoclase-porphyry) have been described, sometimes under the name trachyte, from several British localities. Those which occur as intrusions of Carboniferous age in Haddingtonshire[3]

[1] Pirsson, 20*th Ann. Rep. U. S. Geol. Sur.* part III (1900) 513–515.

[2] *Journ. Geol.* (1899) vii, 108–109.

[3] Hatch, *Trans. Roy. Soc. Edin.* (1892) xxxvii, 123–125, pl. I, figs. 3 4; II, fig. 1; Bailey, *Geology of E. Lothian* (*Mem. Geol. Sur. Scot.* 1910) 128–130.

are in general non-porphyritic. The ferro-magnesian mineral is a green soda-bearing augite, and the felspar which makes the bulk of the rocks must also be rich in soda. Such are the occurrences at North Berwick Law (fig. 38, *A*) and the Bass Rock. A little interstitial analcime is sometimes seen, and the former presence of some nepheline has been conjectured. Other rocks with abundant porphyritic felspar may be named orthoclase-porphyries. A good example occurs at Barbay on

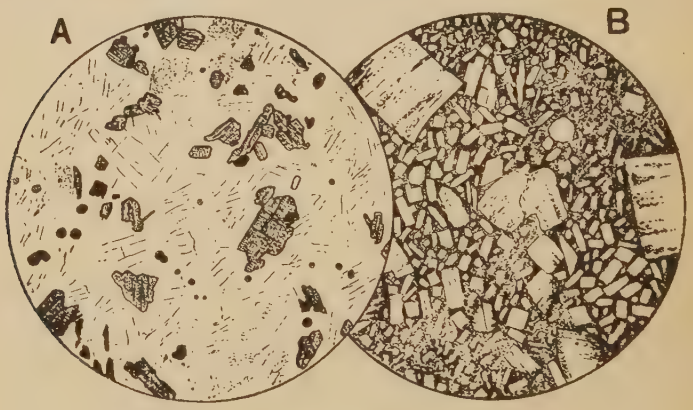

FIG. 38. ORTHOPHYRES, SCOTLAND; ×20.

A. North Berwick Law; with crystals of green augite.

B. Middle Eildon Hill, near Melrose; with interstitial patches of deep blue, nearly opaque, riebeckite.

the island of Great Cumbrae, Firth of Clyde[1]. The ground-mass has the typical orthophyric structure. A few orthophyres are found among the Tertiary intrusions of the West of Scotland. One from Skye contains biotite (fig. 39, *A*), and another from Scalpay has greenish brown hornblende[2].

In an orthophyre from Middle Eildon Hill, Melrose[3], the

[1] Tyrrell, *Pr. Roy. Soc. Edin.* (1917) xxxvi, 293.
[2] *Tert. Ign. Rocks Skye* (1904) 287–289.
[3] Barron, *G. M.* 1896, 376; Lady McRobert, *Q. J. G. S.* (1914) lxx, 309.

coloured silicate is a deep blue riebeckite, which occurs in little patches between the felspar crystals (fig. 38, *B*). Another example, with a microporphyritic structure occurs on Holy Island, near Arran[1].

The typical *bostonites* occur at Marblehead Neck near Boston, Mass.[2], in the Adirondacks[3], near Montreal, and elsewhere as dykes in connection with nepheline-syenite or other

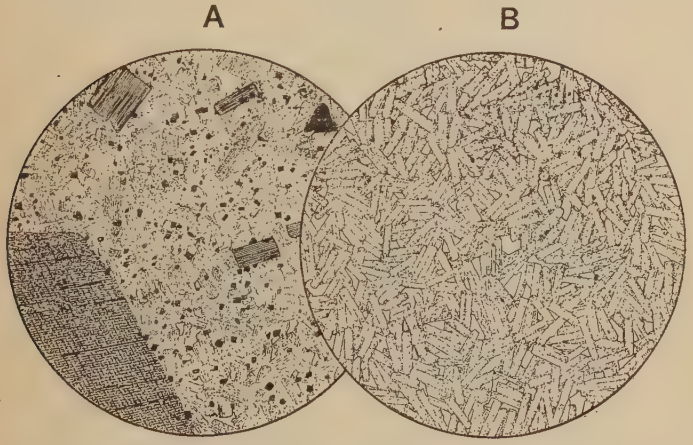

FIG. 39. FELSPATHIC ROCKS, SKYE; ×20.

A. Biotite-Orthophyre, Allt a' Mhaim, N. of Cuillin Hills: consisting of orthoclase with the orthophyric habit and biotite.

B. Bostonite, near Elgol: essentially of little felspar crystals with a small amount of interstitial quartz.

plutonic rocks, and especially in intimate association with dykes of lamprophyre (camptonite). The bostonites consist essentially of felspar, quartz being never abundant and the

[1] Tyrrell, *G. M.* 1913, 305–306.

[2] Wadsworth, *Proc. Bost. Soc. Nat. Hist.* (1881) xxi, 290; Sears, *Bull. Mus. Comp. Zool.* (1890) xvi, 169–171; Washington, *Journ. Geol.* (1899) vii, 293.

[3] Kemp and Marsters, *Trans. N. Y. Acad. Sci.* (1891) xi, 14–16; *Bull. No.* 107 *U. S. Geol. Sur.* (1893) 18–22.

ferro-magnesian silicates typically absent. Phenocrysts are scarce or wanting, the bulk of the rock being a ground-mass of little felspar rods, often with partial flow-disposition and recalling the structure of the trachytes (fig. 40, *A*). In many examples a high percentage of soda, with little or no plagioclase evident, points to a soda-orthoclase or anorthoclase, and indicates an affinity with the ceratophyres. Rocks corresponding more or less closely with these occur on Great Cumbrae, in the

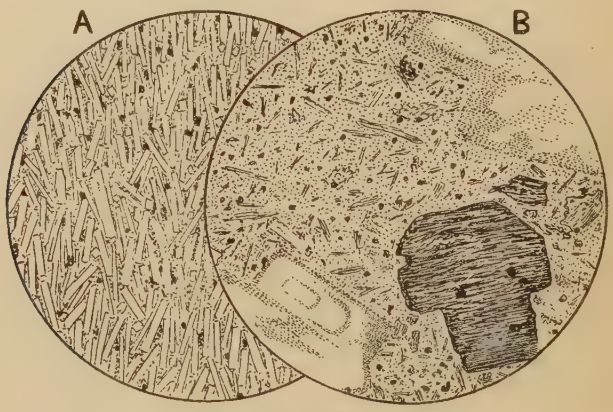

FIG. 40; ×20.

A. Bostonite, Marblehead Neck, Massachusetts; consisting essentially of little crystals of felspar (anorthoclase) with fluxional arrangement.

B. Mica-Porphyrite, Colvend, near Dalbeattie, Kirkcudbrightshire; with phenocrysts of zoned plagioclase and decaying biotite.

Limerick district, and near Kilbride in Co. Mayo[1]. Among the Tertiary intrusions of Skye[2] a bostonite makes the central part of a composite sill near Broadford, and bostonite dykes are found near Elgol in the Strathaird peninsula (fig. 39, *B*).

Among the Devonian intrusions of the Christiania district

[1] Gardiner and Reynolds, *Q. J. G. S.* (1912) lxviii. 92–93.
[2] *Tertiary Igneous Rocks of Skye* (1904) 227, 289–290.

occur the singular rocks known as *rhomb-porphyry* (Ger. Rhombenporphyr, fig. 42, *A*). The phenocrysts of potash-soda-felspar, with their unusual crystallographic development, have been alluded to above. The crystals are often rounded and corroded, and they contain numerous inclusions of materials like the ground-mass. Some of the rocks contain pseudomorphs after olivine. The holocrystalline ground-mass consists of short prisms of felspar (probably orthoclase) with little granules of augite. Apatite is often plentiful, and grains of titaniferous iron-ore occur. In the same district there are lavas of like characters, though with finer texture, and these are common as boulders in the Eastern Counties of England.

The name *ceratophyre* has been employed to denote hypabyssal (and often volcanic) rocks which are composed mainly of a sodic felspar, with little or no quartz. Most of these rocks have suffered much from secondary changes, as is shown by disseminated calcite and iron-oxides, and there is reason for believing that albite has often replaced some more calcic felspar. As a fresh rock composed wholly of soda-felspar, an albite-porphyry has been recorded from Beinn Bràghaid in Sutherland[1], containing albite phenocrysts in a ground-mass essentially of the same mineral, with no other constituent.

The monzonites, like the syenites proper, have their porphyritic equivalents, characterized by the association of orthoclase and a soda-lime-felspar as chief constituent minerals. A good *quartz-monzonite-porphyry* occurs at Cushendun in Antrim, containing abundant crystals of oligoclase, each bordered by a fringe of microperthite. The rest is of quartz and felspar, chiefly orthoclase, with small idiomorphic crystals of hornblende. Doubtless many of the rocks designated porphyrites are in reality of monzonitic composition, but, in the absence of a chemical analysis, it is often difficult to determine the nature of the felspar in a fine-textured ground-mass.

The name *tinguaite* is given to rocks which have the composition of the (plutonic) nepheline-syenites and the (volcanic)

[1] Heddle, *Min. Mag.* (1884) v, 141.

phonolites, with structural characters which place them between those two families. Such rocks are associated with nepheline-syenites in Massachusetts (Essex Co.), Arkansas[1] (fig. 41, *A*) and other countries. Phenocrysts of orthoclase, often with marked tabular habit and with the characters of sanidine, are embedded in a fine-textured holocrystalline ground-mass of orthoclase with nepheline, ægirine, *etc.* This ground is typically allotriomorphic: when the little felspars take on the lath-shape with fluxional arrangement, the rocks do not differ essentially from phonolites. There may be phenocrysts of nepheline, and in one type (leucite-tinguaite) large pseudomorphs of orthoclase and nepheline occur in the form of leucite. This latter type, with pseudomorphs up to 6 inches in diameter, is found at Beemerville in New Jersey[2], and in Arkansas (Magnet Cove)[3] and Montana[4]. A tinguaitic rock at Pickard's Point, Mass.[5], contains analcime and nepheline as the main elements of its ground-mass, and this analcime is considered to be a primary mineral[6]. Tinguaites occur at Kosciusko, New South Wales[7] (see fig. 41, *C*); and a porphyritic variety, with marked flow-structure, comes from Port Cygnet, Tasmania (fig. 41, *B*); while Marshall[8] has described several tinguaite dykes from the Dunedin district of New Zealand.

Coming now to rocks of dioritic affinities, including tonalitic and monzonitic, we find abundant material among the dykes and sills which occur as satellites of the Caledonian intrusions ('Newer Granites' *etc.*) of the Highlands[9] and Southern Uplands of Scotland and the Old Red Sandstone intrusions of Argyllshire

[1] J. F. Williams, *Igneous Rocks of Arkansas*, vol. ii of *Ann. Rep. Geol. Sur. Ark.* for 1890, 100–106; Washington, *Journ. Geol.* (1899) vii, 119–121.

[2] Wolff, *Bull. Mus. Comp. Zool. Harvard* (1902) xxxviii, 273–277.

[3] J. F. Williams, *l.c.* 277–286.

[4] Pirsson, *A. J. S.* (1895) l, 394–398; *Bull.* 237 *U. S. Geol. Sur.* (1905) 126–130.

[5] Sears, *Bull. Essex Inst.* (1893) xxv.

[6] Washington, *A. J. S.* (1898) vi, 182–186.

[7] David and Guthrie, *Pr. Roy. Soc. N. S. W.* (1901) xxxv, 347–382. For other tinguaites see Card and Harper, *Rec. Geol. Sur. N. S. W.* (1905) viii, 36–42.

[8] *Q. J. G. S.* (1906) lxii, 394–397, pl. xxxvii, fig. 2, xxxviii, fig. 1.

[9] See *Memoirs* of Geol. Sur. Scot.

and the Cheviots. Some of the larger masses are of *diorite-porphyrite*, and indeed a gradual transition is sometimes seen from a granitoid structure in the interior of a mass to porphyritic types with fine-textured ground-mass at the margin. The ferro-magnesian constituent of the diorite-porphyrites is most commonly hornblende (Glen Fyne district, Glencoe, *etc.*), less

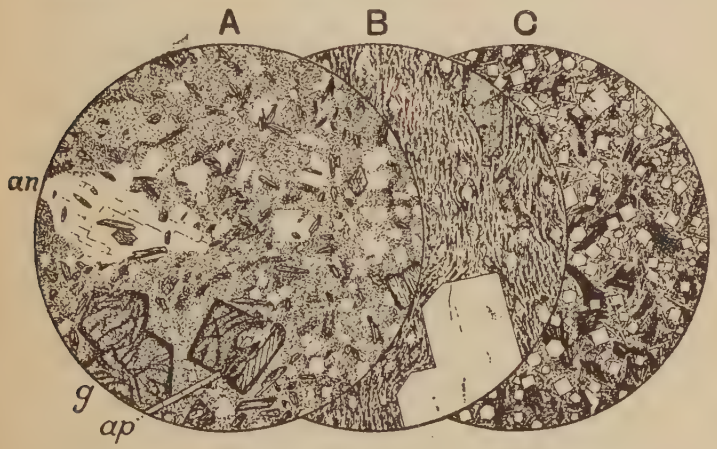

FIG. 41. TINGUAITES; ×20.

A. Hot Springs, Arkansas. The constituents are green ægirine-augite, nepheline, turbid felspar, and interstitial patches of clear analcime (*an*): as accessories brown melanite garnet (*g*) and apatite (*ap*).

B. Port Cygnet, Tasmania: showing phenocrysts of sanidine and ægirine-augite in a fluxional ground-mass of nepheline, ægirine-augite, and sanidine.

C. Kosciusko, New South Wales: composed of nepheline, ægirine, and slender sanidine crystals, with some interstitial glass.

frequently biotite (Glen Tromie in Upper Strathspey), the latter mineral characterizing rather the more acid types. Some more basic types contain augite and exceptionally a rhombic pyroxene (Glen Nant, near Loch Awe).

The same remarks concerning the occurrence of the several ferro-magnesian minerals apply generally to the *porphyrites*

which are so numerous in many parts of the Highlands. The felspar phenocrysts are often oligoclase in the more acid rocks, andesine or labradorite in the more basic. The phenocrysts of plagioclase and the coloured minerals, and more rarely corroded pyramids of quartz, may be crowded together or only sparsely scattered through the rock. The ground-mass is of predominant

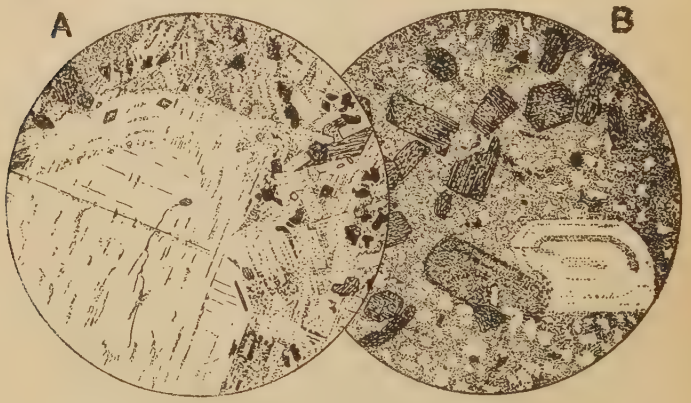

FIG. 42; ×20.

A. Rhomb-Porphyry, dyke, Trosterud, near Christiania: showing a large phenocryst of cryptoperthite, with inclusions, in an orthophyric ground-mass of orthoclase, augite, magnetite, and some apatite and sphene.

B. Hornblende-Porphyrite (Diorite-Porphyrite), sill, N. of Loch Assynt, Sutherland: showing phenocrysts of hornblende and plagioclase in a felspathic ground-mass with some quartz.

plagioclase, with quartz and orthoclase in the more acid types. When these latter minerals enter, the structure is often allotriomorphic, either visibly microcrystalline or cryptocrystalline. When plagioclase greatly preponderates, it is in more or less idiomorphic crystals or microlites.

The Galloway dykes[1] are mostly *mica-hornblende-porphyrites*.

[1] Teall, *Mem. Geol. Sur. Scot., Expl. Sh.* 5 (1896) 44–45, and *Silur. Rocks Scot.* (1899) 626–627.

The phenocrysts are of zoned plagioclase in large individuals, green hornblende and brown biotite, both in good crystals, and sometimes corroded grains of quartz, while the fine-textured ground-mass contains quartz and orthoclase in addition to the other minerals named. In some varieties the hornblende is almost or quite wanting (fig. 40, *B*).

Numerous *mica-porphyrite* dykes occur in the Cheviots[1]. The felspar phenocrysts (oligoclase-andesine) are frequently rounded, and show Carlsbad- and albite-twinning. The biotite-flakes are often bent, and sometimes show a resorption border. A colourless augite may also occur, and magnetite and apatite are minor constituents. The ground-mass is microcrystalline, fine-textured, and often obscured by decomposition. Quartz plays a variable part in it, and there are some transitions to granophyre and quartz-porphyry.

Somewhat different types are found in the Assynt district of Sutherland. One which makes some large sills on Canisp is relatively rich in a sodic felspar. It contains large, frequently broken, phenocrysts of albite-oligoclase, and orthoclase also occurs, sometimes intergrown with the plagioclase. The dominant coloured mineral is biotite. In the same district occur numerous *hornblende-porphyrites*[2]. Here the hornblende is green and in very perfect crystals, often twinned: they sometimes show zonary colouring, and are occasionally hollow. A colourless augite in imperfect crystals sometimes accompanies the hornblende. The plagioclase phenocrysts show strong zonary banding between crossed nicols. Magnetite and apatite are present sparingly. The microcrystalline ground-mass is of felspar with subordinate quartz (fig. 42, *B*). These rocks are part of a variable set of intrusions. On the one hand is a non-porphyritic and coarser-textured type with allotriomorphic felspar (diorite), on the other a type with more abundant hornblende in two generations and with a 'panidiomorphic' ground-mass, which falls into the lamprophyre family (Spessart type, Chap. XI).

[1] Watts, *Mem. Geol. Sur. Eng. and Wales, Expl. Sh.* 110 *S.W.* (1895) 62–63; Kynaston, *Tr. Edin. G. S.* (1899) vii, 398–402.

[2] Teall, *G. M.* 1886, 346–350.

Another hornblende-porphyrite of basic composition is seen in the Mawddach valley, near Dolgelly. It contains large and rather irregularly bounded twin-crystals of brown hornblende in a much decomposed matrix. Hornblende-porphyrites occur also at Rhobell Fawr and in the Arenig district[1], where the hornblende crystals, with good outlines, are mostly replaced by epidote and other secondary products.

[1] Fearnsides, *Q. J. G. S.* (1905) lxi, 632.

CHAPTER X

DOLERITES

The larger intrusive bodies of hypabyssal pyroxenic rocks, whether intermediate or basic in composition, have petrographical features which characterize them as a group with considerable individuality. It is to these rocks that we shall apply the name dolerite. Like their plutonic equivalents, the gabbros, they are holocrystalline and typically non-porphyritic, but they differ from the normal gabbros in their less coarse texture, in the absence of diallagic and other 'schiller' structures, and often also in the mutual relations of the felspar and augite which are their two chief constituents. In these respects there are, however, transitions between the two sets of rocks.

The dolerites occur as large dykes, sills, and laccolitic or other masses. Smaller intrusions of rocks having a similar chemical composition commonly have more of the petrographical characters of volcanic rocks. For these we shall retain the names andesite, basalt, *etc.*, and they will be excluded from this place.

The name 'diabase' is in part synonymous with dolerite. This term, however, is open to objection, since it has been, and still is, employed in different senses. By the German school it is restricted to the older rocks, whether hypabyssal or volcanic, dolerite and basalt being terms reserved for rocks of Tertiary or later age. Allport[1] showed conclusively that such a distinction corresponds with no real difference between the older and the newer rocks, and he abandoned the name diabase in favour of dolerite for all. The rocks so designated by Allport include some of the hypabyssal and others of the volcanic type. English writers have followed him in admitting no criterion of geological age into their classification and nomenclature, but some of them have inconveniently employed the name diabase for a more or less decomposed dolerite.

[1] *Q. J. G. S.* (1874) xxx, 565–566.

According to the absence or presence of olivine, the rocks of the present family are often divided into *dolerites* and *olivine-dolerites*. Olivine is in general found in the more basic members of the family, but this division does not correspond very exactly with the chemical division into intermediate (or sub-basic) and basic. By the presence of some other special mineral we may distinguish such types as *quartz-dolerite*, *hypersthene-dolerite*, *analcime-dolerite*, *etc.*

Constituent minerals. The *felspars* of the dolerites range from oligoclase to anorthite in different examples, but varieties of *labradorite* are the most common. The crystals have a strong tendency to idiomorphism, with columnar or sometimes tabular habit. Twin-lamellation on the albite law is universal, and is often combined with Carlsbad-twinning, but the pericline law is not so common. Zonary growth is not often shown. Primary inclusions are not common, except glass-cavities and needles of apatite. Decomposition gives rise to calcite-dust, to finely divided material, which may be mica, to zeolites (fig. 43), or to granular epidote. The crystals also become charged with strings and patches of green chloritic substances, probably derived in part from the pyroxene. Primary *analcime* occurs in certain types.

The common pyroxenic constituent is an *augite*, usually without crystal-outlines. It varies in thin slices from brown to nearly colourless, or in certain relatively alkaline types shows a purplish tinge with sensible pleochroism. Zonary and 'hour-glass' structures are sometimes seen. The orthopinacoidal twin is common, and in some gabbroid types a fine basal lamination in addition. The commonest decomposition-products are pale green, fibrous or scaly aggregates of serpentinous and chloritic substances. The former may be recognized by their low refractive index and moderately high birefringence; the latter are usually very feebly birefringent or sensibly isotropic, and show distinct pleochroism. Another change to which augite is subject is that which results in a light green 'uralitic' hornblende. This is usually, but not always, fibrous in structure.

Some dolerites contain *bronzite* in addition to augite. It is in more or less idiomorphic crystals, with faint pleochroism,

and gives rise by alteration to pseudomorphs of light green fibrous bastite. Only occasionally does *hornblende* appear as an original constituent. It seems to be characteristically a brown variety. Brown *biotite* is also a rare accessory.

The *olivine*, which occurs in very many dolerites, builds more or less rounded idiomorphic crystals or grains, sensibly colourless or very pale. It has the same mode of alteration as in the olivine-gabbros and peridotites.

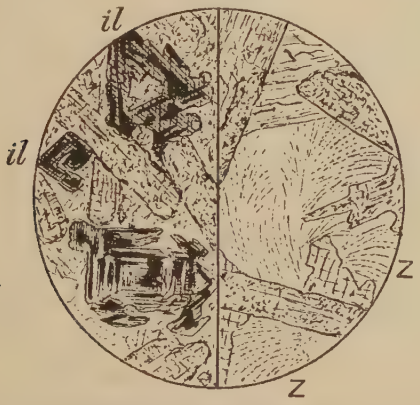

FIG. 43. DECOMPOSING DOLERITE, DENEIO, NEAR PWLLHELI, CAERNARVONSHIRE; × 20.

This shows decomposing felspar crystals and ophitic augite, with ilmenite-skeletons (*il*), encrusted with leucoxene, and patches of radiating fibres of a zeolitic mineral (*z*).

A little *quartz* is found in some of the less basic dolerites, occurring interstitially. Whether it is original or a decomposition-product is sometimes difficult to decide, but when the mineral forms part of a micrographic intergrowth with felspar its primary nature may safely be assumed.

The iron-ores, which, in contrast with some gabbros, the dolerites contain abundantly, include *ilmenite* and *magnetite*. They are very commonly associated, and some so-called titaniferous magnetite has been supposed to be a minute inter-

growth of the two. They are easily distinguished when they occur as crystals or skeleton-crystals. In most cases the ilmenite has given rise to more or less of its characteristic decomposition-product, grey cloudy masses of semiopaque leucoxene (fig. 43). The dolerites are poor in accessory minerals, but needle-like crystals of *apatite* are almost universally present, sometimes in abundance, though often capriciously distributed.

Structure. As regards structure, the dolerites offer a contrast to most plutonic rocks, owing mainly to the fact that the crystallization of the felspar has preceded that of the dominant ferro-magnesian constituent. As seen in a slice, the columnar crystals of felspar show more or less elongated sections, with no law of arrangement, and around or between these the augite is moulded. The last-named mineral in most cases distinctly wraps round the felspar crystals, and often forms plates of some extent, enclosing many of them. This is known as the *ophitic* structure (figs. 44, *A* and 45, *A*). In other cases the augite tends to form more or less rounded grains embedded in a plexus of lath-shaped felspars, adjacent grains not being parts of one crystal but showing different orientations (fig. 44, *B*). This is what Judd[1] styled the *granulitic* structure, and is due to movement towards the end of the process of consolidation. In both types, if olivine is present it is always idiomorphic towards the augite, but may be penetrated by the felspar prisms. Only exceptionally does the augite have idiomorphic shape (fig. 44, *C*). The rhombic pyroxene is constantly of earlier crystallization than the augite, and may show good outlines. The iron-ores are often idiomorphic, but magnetite may be in part later than the felspar.

A porphyritic character, due to the development of relatively large crystals of felspar at an early stage, is not common: it is sometimes connected with an increasing fineness of texture of the rock on approaching the edge of the intrusive mass. Other occasional marginal peculiarities are flow-phenomena, vesicles or amygdales, and the development of a glassy base or sometimes of variolitic and allied structures.

[1] *Q. J. G. S.* (1886) xlii, pp. 68, 76, and figs. pl. v.

Leading types. One type of *quartz-dolerites* is represented by a group of sills in the Carboniferous of the Edinburgh district[1], the Bathgate and Linlithgow Hills[2], the Kilsyth Hills in Stirlingshire[3], *etc.*, with numerous dykes. The Whin Sill[4], extending from the Northumberland coast to the Eden Valley, belongs to the same group. The augite, only partly ophitic in

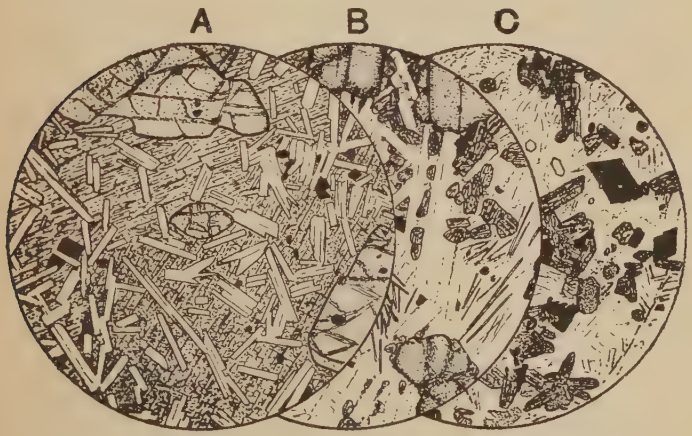

FIG. 44. STRUCTURES OF OLIVINE-DOLERITES; ×20.

A. Tobermory, Mull: with typical ophitic structure.

B. Muckraw, Linlithgow: augite granulitic, with tendency to idiomorphism; abundant needles of apatite.

C. Rowley Regis, near Birmingham: augite in idiomorphic crystals.

habit, is of a pale brown tint, and often shows twinning and the salite structure. In the coarser varieties of rock it is commonly accompanied by a rhombic pyroxene in idiomorphic crystals, often converted to bastite, and a little brown horn-

[1] Flett, *Geology of Edinburgh* (*Mem. Geol. Sur. Scot.* 1910) 301–308.

[2] Falconer, *Tr. Roy. Soc. Edin.* (1906) xlv, 133–147, pl. II, III.

[3] Tyrrell, *G. M.* 1909, 305–309, pl. XII; Bailey, *Geology of Glasgow* (*Mem. Geol. Sur. Scot.* 1911) 146–148.

[4] Teall, *Q. J. G. S.* (1884) xl, 640–657, pl. XXIX; also *Brit. Petr.* pl. XIII, fig. 2.

blende and biotite may occur as accessories. The felspar is usually a labradorite bordered with oligoclase. In the interspaces between these minerals occurs a micrographic intergrowth of quartz with alkali-felspar, largely orthoclase, and quartz may also form irregular grains. The other minerals are magnetite and ilmenite, with leucoxenic alteration, and rather abundant apatite. In small dykes and the margins of sills the rock has a finer texture, and the micrographic patches give place to brown glass or its devitrified representative ('tholeiite' type).

The Penmaenmawr rock, in Caernarvonshire[1], likewise has quartz occurring interstitially in a micrographic intergrowth. In this rock bronzite becomes an essential constituent, being quite as abundant as the pale brown augite. The latter mineral often shows the delicate basal striation already noticed. Biotite is sometimes rather abundant. The structure of the rock is rather granulitic than ophitic, and it usually shows some approach to the characters of volcanic rocks in the occurrence of more than one generation of felspar. Some of the latest shapeless crystals are to be referred to orthoclase.

The numerous sills of Ordovician age in Caernarvonshire[2] are of *dolerite without olivine*, and have almost universally the ophitic structure. The felspar gives lath-shaped or rectangular sections from ·05 to ·5 inch long, with albite- but only occasionally pericline-lamellation: it often has extinction-angles indicating labradorite and neighbouring varieties. The augite is pale brown to almost colourless, and very rarely shows any approach to idiomorphism. Besides the commoner decomposition-products, there is often a fibrous colourless hornblende, fringing the augite but occupying the place of destroyed felspar, *etc.* The iron-ores include both magnetite and ilmenite, often together, and apatite is locally plentiful. Rhombic pyroxene is wanting, as well as olivine, while original hornblende and quartz are practically absent, and biotite very exceptional. The dolerites of similar age in Wicklow are also free from olivine, and are probably of more acid composition, some of them

[1] *Bala Volc. Ser. Caern.* (1889) 65; Teall, *Brit. Petr.* pl. xxxv, fig. 2.
[2] Harker, *Bala Volcanic Rocks of Caernarvonshire* (1889) 79–86.

containing quartz. They are characterized by a partial or even total conversion of the ophitic augite into hornblende, with other changes ascribed to dynamic metamorphism[1].

Dykes of dolerite free from olivine are frequent in the older rocks of the North-West Highlands of Scotland[2]. They are composed of felspar, pale augite with a subophitic habit, and titaniferous iron-ore. There is often a green hornblende in addition, but this is probably in all cases due to metamorphism. Enstatite is often a constituent of these rocks, and in one type quartz occurs (Loch Glencoul).

From the Breidden Hills, in Montgomeryshire, Prof. Watts[3] has described altered ophitic dolerites, in which a rhombic pyroxene, represented by serpentinous pseudomorphs, is sometimes more plentiful than the augite. Such rocks may be styled *hypersthene-dolerites*. Dolerites carrying hypersthene or bronzite in addition to augite occur in the Shelve district of Shropshire, in the neighbourhood of Tremadoc, and about Arenig Fawr. In the last Prof. Fearnsides[4] proved the felspar to be andesine, and such rocks are clearly assignable to the less basic section of the dolerite family, corresponding with pyroxene-andesites rather than with basalts in the volcanic division. In these Arenig intrusions the habit of the augite may be ophitic or subophitic or partly idiomorphic. Ilmenite, with leucoxenic alteration, is a noticeable constituent.

Numerous *olivine-dolerites* are associated with the Carboniferous strata of the Midlands. Good examples are seen in the Clee Hills, Shropshire[5]. The rock of Pouk Hill[6], near Walsall, is an ophitic variety. In that of Rowley, near Birmingham, the augite occurs in little grains, and tends to be idiomorphic[7]

[1] Hatch, *G. M.* 1889, 263–265.

[2] Teall, *Q. J. G. S.* (1885) xli, 135, 146; *Brit. Petr.* pl. xix, fig. 1 (Scourie, Sutherland); *Geological Structure of N. W. Highlands* (*Mem. Geol. Sur.* 1907) 89–96.

[3] *Q. J. G. S.* (1885) xli, 544.

[4] *Ibid.* (1905) lxi, 630–631.

[5] This and many other British examples were noticed by Allport, *Q. J. G. S.* (1874) xxx, 529–567.

[6] Watts, *Pr. Geol. Ass.* (1898) xv, 397–400.

[7] Teall, *Brit. Petr.* pl. xi.

(fig. 44, *C*), or again there is a micrographic intergrowth of augite and felspar[1]. In this rock are relatively acid segregation-veins, in which part of the felspar is orthoclase[2]. Ophitic olivine-dolerites occur again in Derbyshire[3], and in some of these Dr Arnold-Bemrose[4] has described certain peculiar pseudomorphs after olivine. Other examples are found abundantly in the Carboniferous districts of Scotland. These

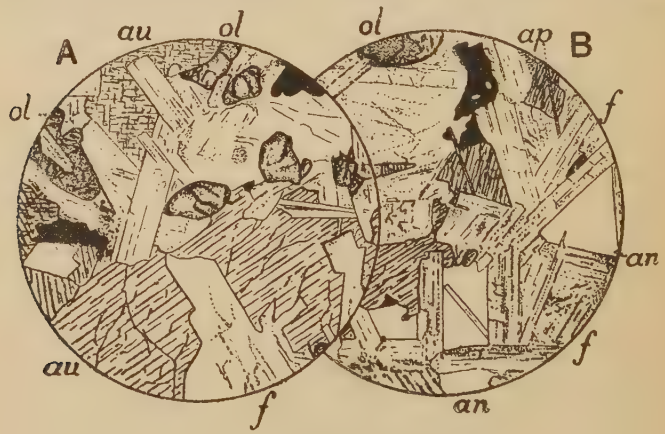

FIG. 45. OLIVINE-DOLERITES; ×20.

A. Fair Head, Antrim: showing typical ophitic structure on rather a coarse scale. Note that the olivine is in part moulded on the felspar.

B. Dippin, Arran: Crinan type, with interstitial patches of clear primary analcime (*an*): ophitic augite of the purplish pleochroic variety.

include types with conspicuous phenocrysts of olivine, augite, and labradorite, the relative amounts of the several porphyritic minerals varying between wide limits.

A great group of olivine-dolerite sills is found in the Inner Hebrides and in Antrim, intruded mostly among the Tertiary

[1] Teall, *Brit. Petr.* pl. XXIII, fig. 2.

[2] Waller, *Midl. Natst.* (1885) viii, 261–266.

[3] Teall, *Brit. Petr.* pl. IX ; Arnold-Bemrose, *Q. J. G. S.* (1899) lv, pl. XX, figs. 1–3.

[4] *Q. J. G. S.* (1895) li, 613–616, pl. XXIV.

basalts[1]. These rocks consist of olivine, felspar (usually a basic labradorite), pale brown augite, magnetite, and a little apatite. The structure is, as a rule, typically ophitic (figs. 44, *A*, and 45, *A*). A porphyritic variety is found on Roineval and elsewhere in Skye[2] and more abundantly in Canna[3]. This encloses crystals of labradorite up to an inch in length.

The basic dykes of the British Tertiary igneous region exhibit much more variety than the sills. The ophitic type of olivine-dolerite is common, but rocks devoid of olivine are also frequent, and there is considerable variety of microstructure. The porphyritic character is much more often met with in the dykes than in the sills. Some dykes probably of this age occur outside the generally recognized area of Tertiary igneous activity, *e.g.* on the Menai Straits. These are for the most part without olivine, and some of them are andesitic rather than basaltic dolerites, while the smaller ones have rather the character of augite-andesites.

Finally we have to remark that some olivine-dolerites show teschenitic affinities by the presence of analcime of primary origin. This mineral is found in certain rocks of the English Midlands (Clee Hills), and in a rather widely distributed type on the western coast and isles of Scotland it becomes abundant, and warrants the distinctive name of *analcime-dolerite* (Crinan type)[4]. At the same time the ophitic augite has the characteristic purple tint, with pleochroism, and sometimes shows zonary and hour-glass structures. The felspar is a labradorite, but often zoned. The analcime is always the latest crystallized mineral, filling the interspaces or sometimes occupying steam-vesicles. This type of rock is well illustrated by sills in the southern part of Arran[5]. Besides the ophitic type (Dippin, fig. 45, *B*), there is one very rich in zeolites and with idiomorphic augite, which approaches more nearly to the teschenites (Clauchland Hills).

[1] *Tert. Ign. Rocks Skye* (*Mem. Geol. Sur.* 1904) 247–250.
[2] *Ibid.* 262–264. [3] *Geology of Small Isles* (1908) 124–126.
[4] Flett, *Geology of Knapdale* (*Mem. Geol. Sur. Scot.* 1911) 116–118; *Geology of Colonsay* (1911) 42–43.
[5] *Geology of N. Arran* (*Mem. Geol. Sur. Scot.* 1903) 112–114; Tyrrell, *G. M.* 1913, 307–309.

CHAPTER XI

LAMPROPHYRES

The lamprophyres are a peculiar group of rocks occurring typically as dykes or other small intrusions. Chemically the more common types are characterized by containing, with a medium or low silica-percentage, a considerable relative quantity of alkalies, while the oxides of the divalent elements are also well represented. This shows itself by an abundance of brown mica, and indeed the lamprophyres as a family are rich in ferro-magnesian silicates. They are fine-grained rocks, but almost always holocrystalline, and their structure is in some respects peculiar.

Von Gümbel's name lamprophyre was extended by Rosenbusch to cover the various members of this group. The best known varieties are mica-lamprophyres ('mica-traps,' Ger. Glimmertrapp). Of these, two types have long been recognized, a chief point of distinction being the predominance of orthoclase in one and plagioclase in the other. To these types are given the names, respectively, *minette* (a word taken from the miners of the Vosges) and *kersantite* (from Kersanton, near Brest). To these Rosenbusch added two other types for rocks in which the place of biotite is taken by augite or hornblende. He separated those with dominant orthoclase (*vogesite*) from those with dominant plagioclase (*camptonite*). The latter name, however, is restricted to the more melanocratic of the hornblende-plagioclase-lamprophyres, the more felspathic being designated *spessartite*. It should be noted that the criterion of the felspars does not lead in this family to a very natural division, especially when much of the potash in the rocks is present in mica. Moreover the true nature of the felspars present is often obscured in thin slices by the abundance of secondary products.

For most purposes it is perhaps sufficient to distinguish the rocks merely as mica-, hornblende-, and augite-lamprophyres.

There are other types of very basic composition, which are devoid of felspar, including the *monchiquites*, characterized by analcime, and the *alnöites*, containing melilite as an important constituent. These are of rare occurrence. They have affinities with the nepheline-basalts, as has also another non-felspathic and ultrabasic type, *limburgite*, which is largely glassy.

Constituent minerals. The characteristic mineral of those lamprophyres most usually met with is *biotite*, which occurs in hexagonal flakes. The extinction-angle (3° or 4°) is sufficient to show frequently a lamellar twinning parallel to the basal cleavage. The flakes are very commonly bleached in the interior, retaining only at the margin the normal deep brown colour (fig. 46, *A*). With the bleaching there is a certain diminution in birefringence. More rarely we find a dark interior with a pale border, or a dark nucleus and border with a pale intermediate zone. Complete decomposition results in a pale, feebly polarizing substance as a pseudomorph. A greenish chloritic alteration is also found. Iron-oxide separates out, usually as limonite, and other minerals are produced as little wedges or lenticles along the cleavages of the mica (fig. 46, *A*). The titanic acid of the mica separates out as rutile, in fine needles arranged in three sets at angles of 60°: this is well seen in basal sections. The original inclusions of the biotite are apatite, and sometimes magnetite and zircon.

Short columnar crystals of *augite* occur in many lamprophyres, showing sharp outlines with an octagonal cross-section, and sometimes lamellar twinning. When fresh, the mineral is pale green or almost colourless in slices, but it is readily replaced by serpentine, calcite, chlorite, *etc.*, in good pseudomorphs (fig. 46, *C*). In other cases uralitization may be noticed. The augite crystals are sometimes coated with flakes of biotite. The most usual occurrence of *hornblende* is in long well-shaped prisms, frequently twinned, but it has some variety of habit. The colour is brown or sometimes green. The mineral may be converted into a chloritic substance with separation of iron-oxides.

A striking feature in the lamprophyres is that the felspars do not usually occur as phenocrysts. The nature of the felspar

in the more altered rocks can be verified only after removing the carbonates from the slice with dilute acid. The small columnar or tabular crystals of *plagioclase* show albite-lamellation and frequently zonary banding. They often have a kind of sheaf-like grouping. Decomposition, beginning in the interior, gives rise to abundant calcite. The *orthoclase*, and perhaps anorthoclase, build short rectangular crystals, simple or Carlsbad twins, often clouded or with ferruginous staining. The monchiquites have no felspar, but contain *analcime*, always interstitial; while *melilite* is the characteristic mineral of the alnöites. The latter mineral is often idiomorphic, with tabular habit parallel to the basal plane, and may show fibrous or spindle-shaped inclusions parallel to the vertical axis. The low refractive index and very weak birefringence, with straight extinction, suffice to identify the mineral.

Some of the more acid lamprophyres have a certain amount of *quartz*, which is either the latest product of consolidation or is intergrown with a portion of the felspar with micrographic structure.

A common accessory in some lamprophyres, and an essential in certain types, is *olivine*, which builds relatively large perfect crystals, or sometimes groups of rounded grains. It is occasionally found fresh, but very commonly represented by pseudomorphs of carbonates and serpentine (fig. 46, *B*). The iron-ores are not often very abundant, and may be quite wanting. The most usual is *pyrites*, but octahedra of *magnetite* are also found. A constant and abundant accessory is *apatite*, but it is sometimes in such fine needles as to be invisible except by oblique illumination. Sphene and zircon are only exceptionally met with.

Structures and peculiarities. Many of the lamprophyres are non-porphyritic, with a rather exceptional structure due to a strong tendency to idiomorphism of all the constituent minerals. This is the 'panidiomorphic' structure of Rosenbusch. The porphyritic members of the family, again, have a peculiarity, in that the porphyritic character is produced by a recurrence of the ferro-magnesian constituents, not of the felspars. Any recurrence of the latter, and especially of ortho-

clase, is rare, but two generations of biotite or of hornblende are seen in many of the rocks. When olivine occurs, it is in conspicuous crystals, but only of one generation.

Without showing any real flow-structure, the felspars of the rock sometimes have a special grouping in sheaf-like or rudely radiating fashion. Exceptionally orthoclase is moulded on the other constituents: usually it is idiomorphic, save when it builds micrographic structures with quartz. There is little indication of any isotropic residue in the commoner lamprophyres, though in some cases little ovoid vesicles seem to have been filled by glass, now devitrified. In certain of the monchiquites, however, there is some brownish glass in patches among the analcime, and in the allied limburgite type the ground-mass is essentially vitreous.

Grains of quartz and crystals of alkali-felspars are found, though very sparingly, in many mica-lamprophyres. Their sporadic occurrence, and still more some curious features which they invariably present, compel us to regard them as something apart from the normal constitution of the rock and of quasi-foreign origin. The *enclosed quartz-grains* are of rounded form, with evident signs of corrosion, and are seen to be surrounded by a narrow ring or shell due to a reaction between the quartz and the surrounding magma. This shell is probably in the first place of augite, but it is often found to consist of minute flakes of greenish fibrous hornblende or of calcite and chloritic products. The quartz having this mode of occurrence must be distinguished from genuine derived fragments torn from other rocks: these are of irregular form, often complex, and may contain inclusions unknown in the corroded quartz-grains.

The *enclosed felspar crystals* are either orthoclase or a plagioclase rich in soda. The crystals are corroded so as to present a rounded outline, but not reduced to mere round grains. The plagioclase thus corroded is bordered by a narrow margin of orthoclase due to the action of the magma.

Leading types. The best known British examples occur as small dykes and sills in the north of England[1]. The dykes

[1] *G. M.* 1892, 199–206, with numerous references.

are numerous in the southern part of the Lake District, from Windermere to Shap and on to Sedbergh, and they are seen again in the Lower Palæozoic inliers of Ingleton, Edenside, and Teesdale. The rocks are *mica-lamprophyres*, but many of them contain subordinate augite, always in perfect crystals, but often decomposed. The relative proportions of orthoclase

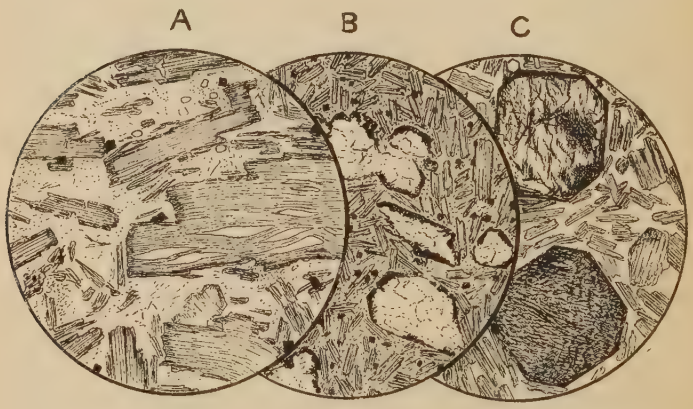

FIG. 46. MICA-LAMPROPHYRES; × 18.

A. Helm Gill, near Dent, Yorkshire. The mica-flakes show each a dark border and a bleached interior. There are also lenticles of secondary products intercalated along the cleavage-planes.

B. Rawthey Bridge, near Sedbergh, Yorkshire. Olivine has been present in abundance, and is now replaced by some rhombohedral carbonate with a border of iron-oxide.

C. St Helier, Jersey. Showing octagonal cross-sections of augite, largely replaced by secondary products.

and plagioclase vary, so that some examples would be named minette and others kersantite, the latter being perhaps the commoner. Good pseudomorphs after olivine are seen in the dykes in the Sedbergh district (fig. 46, *B*).

Scattered quartz-grains with the characteristic corrosion-border occur in many of the dykes; and felspars, both orthoclase and oligoclase, are enclosed sporadically in the Edenside

intrusions, and more abundantly in those to the south of the Shap granite. These rocks show various transitions from typical lamprophyres to a micaceous quartz-porphyry of one of the less acid types, and indeed very different kinds of rocks occur imperfectly mingled in one and the same dyke.

Quartz does not occur as a normal constituent in most of the north-country lamprophyres, though it is found in the transitional rocks just mentioned. In an intrusion at Sale Fell, near Bassenthwaite, quartz occurs partly as interstitial grains, partly in micrographic intergrowth, and the rock shows considerable resemblance to the original kersantites of Brittany.

Mica-lamprophyres are known also from the Isle of Man (Peel Castle), Galloway, many parts of the Highlands of Scotland, and some districts of Ireland.

An augite-bearing minette seems to be one of the commonest types of lamprophyres. It is seen in Cornwall (Trelissick Creek near Falmouth, Newquay[1], *etc.*) and in the Channel Islands (Doyle Monument, Guernsey; St Helier, Jersey, fig. 46, *C*).

More than one type of *hornblende-lamprophyre* is found in the British Isles. Vogesites, consisting essentially of idiomorphic hornblende and orthoclase felspar but often with a little plagioclase (andesine), are found in the Assynt district (fig. 47, *A*) and in numerous parts of the Highlands. In some varieties there is a little quartz in micrographic intergrowth with the orthoclase[2]. The brown hornblende is often accompanied by a pale greenish augite, and sometimes the latter mineral is the more prominent[3]. A typical spessartite consists of idiomorphic brown or greenish brown hornblende and plagioclase, often with a little interstitial orthoclase and sometimes quartz, besides accessory apatite and iron-ores. Such rocks occur in the Assynt district of Sutherland, about Glen Orchy in Argyllshire[4], and elsewhere in the Highlands. Augitic varieties are also found, the augite having a pale green colour.

[1] *Geology of Newquay* (*Mem. Geol. Sur.* 1906) 60–61.
[2] *Geology of Colonsay* (1911) 40.
[3] *Geology of Blair Atholl* (1905) 122–124.
[4] *Geology of Oban and Dalmally* (1908) 119.

Other types of lamprophyre which follow are of more basic composition, and are found commonly as satellites of nepheline-syenites and other alkaline plutonic rocks. The *camptonites* are hornblende-lamprophyres of more melanocratic nature than the spessartites (fig. 47, *B*). Their hornblende is characteristically of a deep red-brown barkevicitic variety, and their pyroxenic constituent is often the purplish pleochroic 'titan-augite' so

FIG. 47. HORNBLENDE-LAMPROPHYRES; ×20.

A. Vogesite, Loyne Bridge, Assynt, Sutherland: composed of green hornblende and orthoclase, with a little plagioclase and magnetite.

B. Camptonite, Mæna, near Gran, Norway. A porphyritic type, with conspicuous crystals of brown hornblende and colourless augite in a ground-mass of brown hornblende, abundant magnetite, and plagioclase felspar.

common in alkaline rocks. Olivine is a frequent constituent. Typical camptonites with these characters are found in Central Ross[1]. Other examples occur in Warwickshire[2]. Various camptonites from the Orkney Isles[3] have abundant augite in

[1] *Geology of Central Ross* (1913) 80.

[2] Allport, *Q. J. G. S.* (1879) xxv, 638–639; Watts, *Pr. Geol. Ass.* (1898) xv, 394; Teall, *Brit. Petr.* pl. xxix, fig. 2 (Marston Jabet).

[3] Flett, *Tr. Roy. Soc. Edin.* (1900) xxxix, 874–887.

addition to hornblende. Some augite-bearing camptonites from the Ardmucknish peninsula of Argyllshire[1] and from the Ross of Mull[2] show a transition to the monchiquite type by the coming in of interstitial analcime.

The typical *monchiquite* has idiomorphic crystals of olivine and augite set in a colourless isotropic base, which seems in

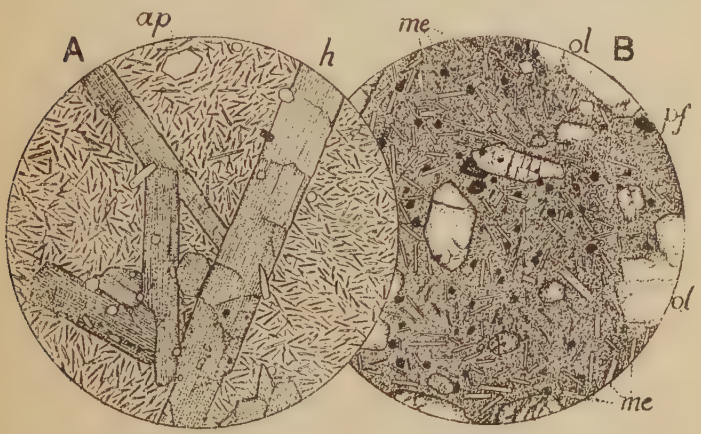

Fig. 48. Ultrabasic Lamprophyres; ×20.

A. Hornblende-Monchiquite or Fourchite, Fernando Noronha, Brazil: contains phenocrysts of apatite (*ap*) and brown hornblende (*h*), with a few of pale augite in other parts of the slide, in a ground-mass of clear analcime crowded with slender hornblende crystals.

B. Alnöite, Spiegel River, Cape Colony. The constituents are deep brown perovskite (*pf*), magnetite, olivine (*ol*), flakes of melilite (*me*), granules of augite, and interstitial glass.

general to be primary analcime. The purplish titaniferous augite often makes porphyritic crystals as well as a crowd of slender prisms. Brown hornblende and sometimes biotite may also be present, and apatite and magnetite are the common accessory minerals. Rocks of this kind are found at Kirkwall

[1] *Geology of Oban and Dalmally* (1905) 125.
[2] *Geology of Colonsay* (1911) 90.

in the Orkneys[1] and Dunnet Head in Caithness[2], on Colonsay[3] (with large crystals of hornblende and biotite), and in other parts of Scotland. A variety from Ardmucknish[4] and East Fife contains large rounded crystals of anorthoclase. The corresponding rocks devoid of olivine have received the name *fourchite*, and these also include types with predominant hornblende (fig. 48, *A*) or biotite. Hornblende-fourchites are recorded from the Ross of Mull and the Orkneys, and one with conspicuous biotite from Colonsay. The ultrabasic affinities of the monchiquites are sometimes emphasized by enclosed nodules of peridotite (near Chepstow, Monmouthshire[5]).

While the colourless base of the monchiquites is commonly identified as analcime[6], Rosenbusch and other petrologists have regarded it as a glass. In the allied type *limburgite* the interstitial base is recognizably a brown glass, and transitional varieties are found in which brown and colourless parts are intermingled. Such rocks occur at Chester's quarry near Haddington[7] and as dykes in the volcanic necks of East Fife[8]. Some of these rocks have probably contained a certain amount of nepheline.

The *alnöites*, originally described under the name melilite-basalt, from Alnö, off the coast of Sweden, are defined by Rosenbusch as olivine-rich biotite-monchiquites with a variable content of melilite and perovskite. The only rocks of this kind known in Britain are those described by Dr Flett[9] from the Orkneys, where they form dykes cutting the Old Red Sandstone and associated with others of camptonite and

[1] Flett, *loc. cit.* 887.
[2] *Geology of Caithness* (1914) 115–116.
[3] *Geology of Colonsay* (1911) 43–45.
[4] *Geology of Oban and Dalmally* (1908) 127.
[5] Boulton, *Q. J. G. S.* (1911) lxvii, 460–476.
[6] Pirsson, *Journ. of Geol.* (1896) iv, 679–690; Evans, *Q. J. G. S.* (1901) lvii, 38–53.
[7] Hatch, *Trans. Roy. Soc. Edin.* (1892) xxxvii, 116–117, pl. i, fig. 1; Bailey, *Geology of E. Lothian* (1910) 107–111.
[8] Flett, *Geology of E. Fife* (1902) 403–404; Mrs Wallace, *Tr. Edin. Geol. Soc.* (1916) x, 348–362, pl. xliii. On the original limburgite of the Kaiserstuhl, Baden, see Bonney, *G. M.* 1901, 411–417.
[9] *Tr. Roy. Soc. Edin.* (1900) xxxix, 892–898, pl. iii, figs. 4–6.

monchiquite. One from Rennibuster, near Kirkwall, has for phenocrysts large irregular plates of biotite, small serpentinized olivines, and some large idiomorphic crystals of augite. The ground-mass consists of abundant small augites of purplish brown colour, idiomorphic melilite, and interstitial matter representing altered glass or perhaps nepheline. Another, from Naversdale near Orphir, has the melilite in allotriomorphic patches, showing peg-structure. The mineral is often replaced by zeolites and calcite. A good alnöite (fig. 48, *B*) comes from Spiegel River, Cape Colony, and the type is represented at other localities in the South African diamond-fields[1]. Another is found at Ste Anne de Bellevue, near Montreal[2]. Here the phenocrysts are brown mica in large and abundant crystals, olivine more or less converted to hæmatite, and augite: the ground-mass is of mica, olivine, augite, magnetite, and melilite, with apatite and perovskite. The melilite is the latest product of consolidation, forming imperfect crystals of tabular habit with the characteristic 'peg-structure.'

[1] Rogers, *Ann. Rep. C. G. H. Geol. Comm.* for 1898, 62; for 1903, 50–51.

[2] Adams, *A. J. S.* (1892) xliii, 269–279.

C. VOLCANIC ROCKS

Under this head we shall treat only the solid rocks of volcanic origin (lavas), reserving the fragmental products of volcanic action for the sedimentary group. With the true extruded lava-flows will be included similar rocks occurring in the form of dykes, *etc.*, in direct connection with volcanic centres, the common feature of all being that they have consolidated from fusion under superficial conditions, *i.e.* by comparatively rapid cooling under low pressure. This mode of origin has given the rocks as a whole characters which place them in contrast with the plutonic group, while the types treated above under the head of 'hypabyssal' have in some respects intermediate characters. Many volcanic outpourings have undoubtedly been submarine, and when these have taken place under a great depth of water the products may be expected to approximate in some measure to the characters of rocks of deep-seated origin. In general, however, the contrast between volcanic and plutonic types of structure is well marked.

The presence of a glassy (or devitrified) residue, though not peculiar to volcanic rocks, is highly characteristic of them, and especially of the more acid members. Other features characteristic of lavas, though not confined to them, are the vesicular and amygdaloidal structures and the various fluxion-phenomena, including flow-lines, parallel orientation of phenocrysts, banding, drawing out of vesicles, *etc.*

The great majority of the volcanic rocks have a porphyritic structure, and their constituents belong to two distinct periods of consolidation, the earlier represented by the porphyritic crystals or 'phenocrysts,' and the later by the 'ground-mass,' which encloses them, and commonly makes up the bulk of the rock. This ground-mass may, and usually does, include some glassy residue or 'base': if the ground is wholly glassy, we have what is termed the 'vitrophyric' structure. The same mineral may occur both among the phenocrysts and as a constituent of the ground-mass. When such a recurrence is found, the crystals of the earlier generation are distinguished from those of the later by their larger size, often by their more

perfect idiomorphism, and in some cases by fracture, corrosion, or other evidence of vicissitudes in their history. The two periods of consolidation were styled by Rosenbusch the 'intratelluric' and the 'effusive,' the former being considered as the result of crystallization prior to the pouring out of the lava, and so under more or less deep-seated conditions. When we speak of the consolidation of a lava at the earth's surface, we must be understood to refer to the ground-mass of the rock. In some few types of lavas the phenocrysts fail altogether, and the effusive period is the only one represented.

The various types will be grouped under families, to be taken roughly in order, beginning with the most acid. It is customary to speak of the several families of lavas as answering to the commonly recognized families of the plutonic rocks – the rhyolites to the granites, the trachytes to the syenites, *etc.* —but such a correspondence cannot be followed out with great exactness. It is certain that a given rock-magma may result in very different mineral-aggregates according as its consolidation is effected under deep-seated or under surface conditions; and in the latter case, moreover, much of the rock produced may consist of unindividualised glass.

It is more especially in the volcanic rocks that the Continental petrologists have insisted upon a division into an 'older' and a 'younger' series ('palæovolcanic' and 'neovolcanic'), an arbitrary line being drawn between the pre-Tertiary lavas and the Tertiary and Recent. This distinction is rejected by the British school, and will find no place in the following pages. The simplified grouping of the volcanic rocks by their essential characters, without reference to their age or supposed age, involves some modification of the double nomenclature in use among the German and French writers. The names employed by them for the younger lavas only will here be extended to all rocks of the same character, irrespective of their geological antiquity. The names applied by the Continental writers to the pre-Tertiary lavas have also been used habitually for hypabyssal rock-types, and may now be restricted to these latter. Some of them (quartz-porphyry, porphyrite, *etc.*) we have already used in this sense.

CHAPTER XII

RHYOLITES

In the rhyolite family we include all the truly acid lavas; rocks of porphyritic or vitrophyric structure, in which alkali-felspars and usually quartz figure as the chief constituent minerals. By the older writers most of these rocks were included, with others, under the large division 'trachyte.' The present family was separated by von Richthofen with the name '*rhyolite*,' expressing the fact that flow-structures are commonly prominent in the rocks. Roth used the term '*liparite*' in nearly the same sense. The Continental petrographers, following their regular principle, use these names for the Tertiary and Recent acid lavas only, the older (pre-Tertiary) being more or less arbitrarily separated and designated by other names (quartz-porphyry, porphyry, *etc.*); and some English geologists have tacitly adopted a like division, calling the older rhyolites, which have often suffered various secondary changes, quartz-felsites, felsites, *etc.*

Some petrologists distinguish between *potash-* and *soda-rhyolites*, according to the predominance of one or the other of the alkalies; but in fine-textured or glassy rocks this difference does not always express itself in the minerals evident. There is, however, a peculiar group of lavas rich in alkalies, especially in soda, the *pantellerites* of Förstner. The more acid of these may be attached to the rhyolite family.

We shall consider briefly the characters of the phenocrysts or enclosed crystals and of the ground-mass. In some rhyolites the phenocrysts occur only sparingly, or may even fail altogether.

Phenocrysts. Among the phenocrysts or porphyritically enclosed crystals of the rhyolites, the most constant are alkali-felspars; both *orthoclase* (including *sanidine*) in tabular or columnar crystals, simple or twinned, and an acid plagioclase, ranging from *albite* to *oligoclase*, in tabular crystals with the

usual twin-lamellation. A parallel intergrowth of the monoclinic and triclinic species is occasionally found. The felspars often contain glass- and gas-cavities, but rarely fluid-pores: such minerals as apatite, magnetite, biotite, *etc.*, may be sparingly enclosed. Certain rocks specially rich in soda (pantellerites, *etc.*) have *anorthoclase*.

Quartz, when present, occurs in dihexahedral crystals, often corroded and with inlets of the ground-mass. Besides occasional inclusions of minerals of early consolidation, it contains glass- but rarely fluid-cavities.

The more basic silicates are not present in great abundance. The most usual is *biotite* in deep brown hexagonal flakes, with only occasional inclusions of apatite, zircon, or magnetite. A greenish *augite* with octagonal cross-section may be present, but *hornblende* is much less common. The 'pantellerites' have the brown triclinic amphibole *cossyrite*, with intense absorption and pleochroism, and the 'comendite' type has *ægirine*.

The most usual iron-ore is *magnetite*, but it is rarely abundant. Needles of *apatite* and minute crystals of highly refringent and birefringent *zircon* may also occur in small quantity. In rarer cases *garnet* is found instead of a ferro-magnesian bisilicate.

Ground-mass and structures. The rhyolites exhibit in their ground-mass a great variety of texture and structure. The texture may be wholly or partly glassy; or cryptocrystalline, often with special structures; or, again, evidently crystalline, though on a minute scale. Further, these several varieties of ground-mass may be associated in the same rock and in the same microscopical specimen. Fluxion is frequently marked by banding, successive bands being of different textures, so that thin layers of glassy and stony or spherulitic nature alternate with one another.

The *vitreous* type of ground-mass alone is found in the *obsidians*[1]. These rocks, colourless or very pale yellow in thin

[1] The less common glassy rocks of the trachyte and phonolite families and of the dacites are also termed obsidian. They are not easily distinguished from the rhyolite-glasses. Some of the rocks styled 'pitchstones' are lavas of the obsidian type, usually of acid composition (*e.g.* the 'Meissen pitchstones,' in Saxony).

slices, afford good examples of structures common to all the natural glasses; especially the *perlitic cracks* (fig. 49) produced by contraction of the homogeneous material, and the *vesicular* structure due to the rock-magma having been distended by steam-bubbles. In extreme cases the cavities are so numerous as to make up the chief part of the volume of the rock, and we have the well-known pumice (Fr. ponce, Ger. Bimsstein). The vesicles are commonly elongated in the direction of flow, and may even be drawn out into capillary tubes. In the older

Fig. 49. Glassy Rhyolite (Obsidian), Telkibanya, near Schemnitz, Hungary; ×20.

Showing sinuous flow-lines traversed by a system of curving perlitic fissures.

lavas vesicles are filled by secondary products, and become amygdales.

In most cases a ground-mass consisting essentially of glass encloses minute bodies known as *crystallites* (fig. 50), which may be regarded as embryonic crystals. They have definite forms, but no perfect crystal boundaries, and the more rudimentary types cannot be subjected to optical tests to determine their nature. The simplest effort at individualisation from the vitreous mass results in 'globulites,' minute spherical

bodies without action on polarized light. They occur in profusion in many obsidians, either uniformly distributed or aggregated into cloudy patches ('cumulites'). From the partial coalescence of a series of globulites, arranged in a line, result 'margarites,' resembling strings of pearls (fig. 50, *A*). A high-power objective (say $\frac{1}{8}$ inch) is often necessary to resolve this beaded structure. Long threads of this nature may extend in the direction of flow but with numerous little twists (fig. 50, *D*).

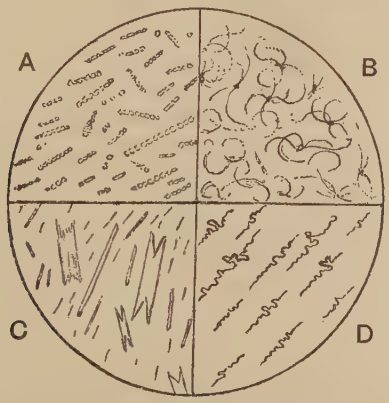

FIG. 50. CRYSTALLITES IN OBSIDIAN.

A. Margarites, Obsidian Cliff, Yellowstone Park; ×400.

B. Trichites, Telkibanya, Hungary; ×100.

C. Longulites and swallow-tailed crystallites, Hlinik, Hungary; ×200.

D. Flow-structure marked by arrangement of twisted trichites, Prabacti, Java; ×200.

Similar threads with curved hair-like form, known as 'trichites,' often occur in groups originating in a common nucleus. These bodies, in which a beaded structure may or may not be observable, seem to belong to a stage of development later than the cessation of flowing movement in the mass (fig. 50, *B*). The small rod-like bodies known as 'longulites,' sometimes slightly clubbed at the ends, may be regarded as built up by the complete union of rows of globulites. They occur in crowds, with a

marked arrangement parallel to the direction of flow. The transition from margarites to longulites is often seen, some of the little rods resolving into beaded strings, while others do not. The larger crystallitic bodies termed 'microlites' are possibly to be conceived as built up from longulites. Various incomplete stages may be observed, the ends of the imperfect microlites having a brush-like form ('scopulites' of Rutley) or being forked in swallow-tail fashion (fig. 50, *C*). Fully developed microlites have an elongated form, and are indeed small crystals, giving the optical reactions proper to the mineral (felspar, augite, hornblende, *etc.*) of which they consist.

An original *cryptocrystalline* or 'microfelsitic' ground-mass is found in some rhyolites, though it seems to be more characteristic of intrusive types (approaching what we have styled quartz-porphyries) than of true surface lavas. It consists in a granular mixture of felspar and quartz on so minute a scale that the individual grains cannot be resolved in a thin slice. There is no doubt, however, that in many old acid lavas a cryptocrystalline ground-mass has resulted from the *devitrification* (Ger. Entglasung) of a rock originally vitreous. The process has often begun along perlitic fissures, or flow-lines, and the successive stages are beautifully displayed in such rocks as the Permian rhyolites ('pitchstones') of Meissen in Saxony. No single criterion can be set up for distinguishing an original from a secondary cryptocrystalline structure. In a rock otherwise fresh, however, there will generally be no reason to suspect devitrification; while, on the other hand, the presence of perlitic cracks is often taken to indicate that the rock in which they occur was originally glassy.

A *microcrystalline* (as distinguished from cryptocrystalline) ground-mass is not very prevalent in true acid lavas, but may occur as bands alternating with glassy or microspherulitic bands, often on a small scale. When an evident microcrystalline structure has been set up as a secondary alteration, it probably indicates, as a rule, something more than the merely physical change of devitrification. It is often connected with an introduction of silica from an external source, and in the resulting microcrystalline mosaic quartz often plays a more

important part than it would do in a normal igneous rock. In some of the partly silicified Ordovician rhyolites of Westmorland a secondary quartz-mosaic still shows clear indication of former perlitic cracks, outlined by dust, as well as the characteristic banding. In these rocks, too, *silicification* has sometimes affected not only the ground-mass but the felspar phenocrysts.

Spherulitic and allied structures. The spherulitic growths which are common in many acid lavas may be conveniently divided into the larger and the smaller. Under the former head we have spherulites, often isolated, with diameters ranging from a fraction of an inch to several inches. They are best studied in certain obsidians, where they are usually of distinctly globular form and with well-defined boundary. The examples which have been most carefully examined, and may be taken as typical, consist mainly of extremely delicate fibres of felspar, arranged radially and on the whole straight, but often forked or branching[1]. In the spherulites of perfectly fresh rocks the space between the fibres is found to be occupied in great part by aggregates of tridymite. In older spherulites, where tridymite is not recognized, quartz may perhaps be considered to represent it. It may often be observed that the flow-lines of the lava pass undisturbed through the spherulites, indicating that the latter crystallized after the cessation of movement. Spherulites are often developed along particular lines of flow, and may coalesce into bands (fig. 51).

These larger spherulites show many special peculiarities in different examples. Sometimes their outward extension has been effected in two or more stages, which are marked by a change in the character of the growth. Again, curious phenomena arise from the formation of shrinkage-cavities (*lithophyses*) in connection with spherulites. Some remarkable examples of lithophyses have been described from the Yellowstone

[1] See Cross, *Bull. Phil. Soc. Washington* (1891) xi, 411–414; Iddings, *ibid.* 445–464, with plates. Similar structures occur in dykes on Druim an Eidhne, near Loch Coruisk, Skye: see Judd, *Q. J. G. S.* (1893) xlix, pl. II, III; Harker, *Tertiary Igneous Rocks of Skye* (*Mem. Geol. Sur.* 1904) 283–286, pl. XI, XII, and XXII, fig. 3.

Park[1] and other districts in the United States[2], from Hungary, and from Lipari[3]. A peculiar feature is the occurrence in the hollows of perfect crystals of the iron-olivine (fayalite), as well as aggregates of tridymite, and in some cases crystals of garnet, topaz, *etc.*

Examination of the older acid lavas shows that the large spherulites are specially susceptible to certain chemical changes. They are often found partly or totally replaced by flint or quartz, while their insoluble decomposition-products remain as

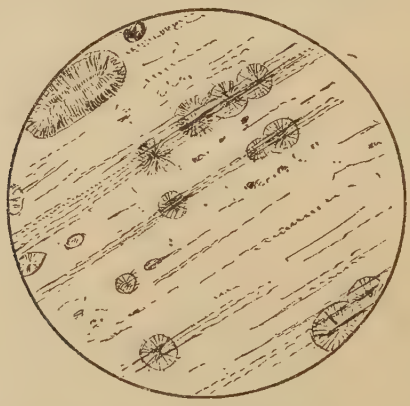

FIG. 51. OBSIDIAN, VULCANO, LIPARI IS.; ×20.

The glassy matrix encloses isolated spherulites with some tendency to coalesce in bands following the direction of flow. The flow-lines pass uninterruptedly through the spherulites.

roughly concentric shells of a chloritic or pinitoid substance. Again, a central hollow is often found, and it is not always clear whether this is due entirely to decomposition or partly represents an original lithophysal cavity[4], nodular structures

[1] Iddings, *Obsidian Cliff*, in *7th Ann. Rep. U. S. Geol. Surv.* (1888) 265–266, pl. XII–XIV; *A. J. S.* (1887) xxxiii, 36–43.

[2] Nathrop, Colorado; see Cross, *Proc. Colo. Sci. Soc.* (1886) 62–66.

[3] Cole and Butler, *Q. J. G. S.* (1892) xlviii, 438–443, pl. XII; Johnston-Lavis, *G. M.* 1892, 488–491.

[4] See especially Cole, *Q. J. G. S.* (1886) xlii, 183–190; (1892) xlviii, 443–445; Parkinson, *ibid.* (1901) lvii, 211–225, pl. VIII.

originating in both ways being represented in many districts. These old nodular rhyolites have been termed 'pyromerides.'

The very minute spherulites commonly occur in large numbers, closely packed together, so as to constitute the chief bulk of particular bands, or even of the whole ground-mass of the rock. This is the *microspherulitic* structure. The true nature of these very minute bodies, as composed of fine fibres of felspar with quartz, is a matter rather inferred than seen in any given case; but the radiate growth is detected by means of the 'black cross,' which each individual spherulite shows between crossed nicols (fig. 52, *C*). These minute spherulites seem to be much less readily destroyed than the larger ones. The *axiolites* of Zirkel seem to be of the nature of elongated spherulites, the fibres radiating not from a point but from an axis; or they may be conceived as representing the coalescence of a row of minute spherulites.

Any evident micrographic structure is not common in the ground-mass of rhyolites, though bands or streaks having this character are sometimes found. A curious feature, first described by Iddings in some obsidians from the Yellowstone Park[1] and rhyolites from the Eureka district of Nevada[2], is the occurrence of porphyritic 'granophyre groups' or *micropegmatite phenocrysts* in a glassy, cryptocrystalline, or microcrystalline ground-mass. In these the quartz is subordinate to the felspar in quantity, and the micrographic groups often show the crystal boundaries of the latter mineral. As a rule, however, there are several felspar crystals grouped together, the whole permeated by wedges of quartz, and the outline is complex or rather irregular[3].

A structure met with in the ground of some rhyolites, and in certain bands of laminated rhyolites, differs essentially from the micrographic, in that it indicates the successive, instead of simultaneous, crystallization of the two constituent minerals.

[1] *7th Ann. Rep. U. S. Geol. Sur.* (1888) 274–276, pl. xv.

[2] *Monog.* xx *U. S. Geol. Sur.* (1893) 375, pl. v, fig. 2.

[3] Compare *Tertiary Igneous Rocks of Skye* (*Mem. Geol. Sur.* 1904) 282, 284–285, pl. xx, fig. 2, where similar peculiarities are described in rhyolitic dykes.

Minute felspar crystals with no orderly arrangement are enclosed in little ovoid or irregular areas of quartz, the whole of the quartz in such a little area being in crystalline continuity. This structure reproduces on a minute scale the ophitic and pœcilitic structures presented by different minerals in other rocks, and G. H. Williams[1] adopted for it the term *micropœcilitic.*

Leading types. The best examples of fresh unaltered rhyolites come from the Tertiary acid lavas of Hungary, the Lipari Isles, and America. In the United States the finest examples of *obsidian* come from Obsidian Cliff in the Yellowstone Park[2]. In special varieties the glassy matrix contains spherulites of some size, isolated or in bands, and remarkable chambered lithophyses, in which occur nests of tridymite and little crystals of the iron-olivine (fayalite). There are also in the Yellowstone Park finely banded *rhyolites*, in which the narrow bands differ in microstructure, some being cryptocrystalline, others microspherulitic or axiolitic. Various types of rhyolites from the Eureka district have also been described by Iddings[3]. These carry a little biotite. In examples described by the same author[4] from New Mexico (Tewan Mts) the ferromagnesian mineral is augite. In these rocks plagioclase felspar is wanting: some contain spherulites and lithophyses. Rhyolites from Custer County, Colorado, have no coloured constituent except a little red garnet[5]. The ground-mass is usually microcrystalline to cryptocrystalline, but sometimes spherulitic. Biotite-bearing rhyolites with porphyritic quartz occur in the Tintic Mts, Utah[6]. Some varieties in the Lassen Peak district, California, are highly spherulitic[7].

Fresh Tertiary rhyolites are not widely represented in the British Isles, but some good examples come from Antrim, and

[1] *Journ. Geol.* (1893) i, 176–179.
[2] Iddings, *7th Ann. Rep. U. S. Geol. Sur.* 249–295; Rutley, *Q. J. G. S.* (1881) xxxvii, 391–396, pl. xx.
[3] *Monog.* xx *U. S. Geol. Sur.* (1893) 374–380, pl. viii.
[4] *Bull. No.* 66 *U. S. Geol. Sur.* (1890) 10–11.
[5] Cross, *Proc. Colo. Sci. Soc.* 1887, 229–233.
[6] Tower and Smith, *19th Ann. Rep. U. S. Geol. Sur.* part iii (1899) 633.
[7] Diller, *Bull.* 148 *U. S. G. S.* (1897) 192.

show a considerable range of microstructure. The glassy type (obsidian) occurs at Sandy Braes, and contains phenocrysts of quartz, with less abundant felspar, in a ground-mass of glass enclosing numerous microlites of felspar (fig. 52, *A*). There is a pronounced perlitic structure, and Prof. Watts[1]

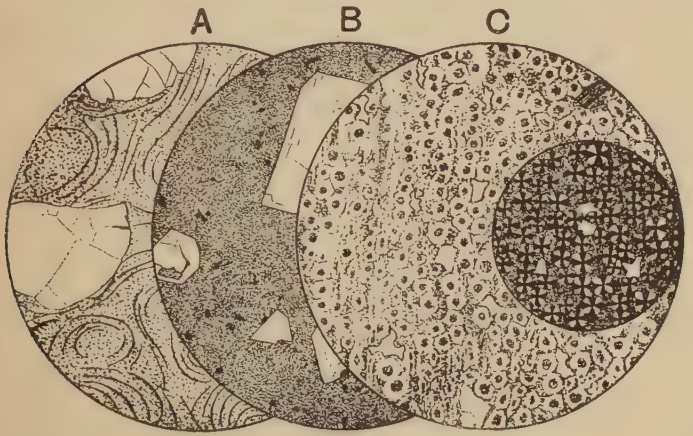

Fig. 52. Rhyolites, Antrim; ×20.

A. Obsidian, Sandy Braes. The phenocrysts are of quartz; the ground-mass a pale brownish glass, crowded with minute felspar microlites, and traversed by perlitic fissures.

B. Rhyolite, Kirkinriola. The phenocrysts are of sanidine and quartz, with a few scattered flakes of biotite and minute crystals of magnetite; the ground-mass a very finely crystalline aggregate of felspar and quartz.

C. Microspherulitic Rhyolite, Cloughwater: consisting essentially of closely packed little spherulites, giving the black cross between crossed nicols, as shown in the small inset circle. The occasional patches of clear quartz are secondary.

has remarked that the fine fissures traverse not only the glass but sometimes also the quartz crystals. Prof. Cole[2] has described also lithoidal varieties from Kirkinriola (fig. 52, *B*),

[1] *Q. J. G. S.* (1894) l, 367–375, pl. xviii.
[2] *Sci. Trans. Roy. Dubl. Soc.* (1896) vi, 77–118, pl. iv.

Templepatrick, *etc.*, and a microspherulitic one from Cloughwater (fig. 52, *C*). Rhyolites are found again between Dromore and Moira, Co. Down. In the Tertiary rhyolites of Fionn-Choire, in Skye, the ground-mass is partly replaced by streaks and lenticles of quartz[1].

The most interesting British rhyolites, however, are those belonging to the Palæozoic and older volcanic groups, and these have doubtless had their pristine characters modified in many instances by *secondary physical and chemical changes*. Allport was the first to give a clear account of some of the old altered volcanic glasses, and to compare them with fresh Tertiary examples. He described what seems to be a devitrified and altered spherulitic rhyolite of pre-Cambrian age from Overley Hill (or the Lea Rock) near Wellington, Shropshire[2]. A few phenocrysts occur, but the bulk of the rock has been a glass enclosing numerous bands of spherulites. The glass is now devitrified, but perlitic cracks, marked by secondary products, are still evident. The spherulites too are for the most part much altered and stained red by iron-oxide.

The Ordovician rhyolites of Caernarvonshire[3] are characterized by the general paucity of any phenocrysts, and especially of those of quartz. Among the scattered felspar crystals, a member of the albite-oligoclase series predominates over orthoclase. Almost the only ferro-magnesian constituent is a little colourless augite, and even this is commonly wanting, though a pale green decomposition-product may perhaps represent it. The usual texture of these old lavas is cryptocrystalline to microcrystalline, sometimes showing fluxion and banding, and occasionally good perlitic cracks. The vesicular structure is not very frequent. In some types the ground is partly micropœcilitic, minute felspar prisms being enclosed in quartz (Penmaenbach, *etc.*). Any approach to a microspherulitic structure of a perfect type is uncommon, but large isolated spherulites are abundant in many localities, and show the

[1] *Tertiary Igneous Rocks of Skye* (1904) 59–61.

[2] *Q. J. G. S.* (1877) xxxiii, 449–460; Teall, *Brit. Petr.* pl. xxxiv, figs. 1, 2.

[3] *Bala Volc. Ser. Caern.* (1889) 18–23. See also Bonney, *Q. J. G. S.* (1882) xxxviii, 289–296, pl. x; Rutley, *ibid.* (1881) xxxvii, pl. xxi, and *Mem. Geol. Sur., Felsitic Lavas* (1885) pl. ii–iv.

various secondary alterations, concentric shell-structure, silicification, *etc.*, to which they are always prone[1]. The siliceous and other nodules which thus arise may reach several inches in diameter. Some of them probably represent true lithophyses[2].

Various types of rhyolites, including some with micropegmatite phenocrysts, occur in the Ordovician of Fishguard in Pembrokeshire[3]; spherulitic and other varieties on Skomer Island[4]; and imperfectly spherulitic types in the Precelli Hills[5]; while examples from Llanrian[6] contain phenocrysts of quartz and orthoclase in a microfelsitic ground-mass. These Pembrokeshire lavas are *soda-rhyolites*, as are others of Ordovician age in the Dolgelly district[7].

Nodular structures, often more or less completely replaced by quartz, are seen also in Westmorland (Great Yarlside). The old rhyolites here resemble in many respects those of like age in Caernarvonshire, but certain flows show a very perfect microspherulitic structure. This is well seen in Long Sleddale[8] and near Great Yarlside. From Dufton Pike, in Edenside, Rutley[9] described and figured rhyolites with a tufaceous structure; and others from the same district show flow brecciation or enclose foreign fragments[10].

Various acid lavas occur in the Ordovician of Ireland. Some from Raheen and other places in Co. Waterford show perlitic and microspherulitic structures[11].

[1] *Bala Volc. Ser. Caern.* 35–39; Cole, *Q. J. G. S.* (1885) xli, 162–168, pl. iv, and (1886) xlii, 185–189, pl. ix; Miss Raisin, *ibid.* (1889) xlv, 247–269.

[2] Cole, *Q. J. G. S.* (1892) xlviii, 443–445, with references.

[3] Reed, *ibid.* (1895) li, 162, pl. vi, figs. 3–5.

[4] Thomas, *ibid.* (1911) lxvii, 185–190; *Geology of Country around Milford* (*Mem. Geol. Sur.* 1916) 30–31.

[5] Parkinson, *Q. J. G. S.* (1897) liii, 465–476, pl. xxxvi.

[6] Elsden, *ibid.* (1905) lxi, 581.

[7] Reynolds, *ibid.* (1912) lxviii, 357–360.

[8] Rutley, *ibid.* (1884) xl, pl. xviii, fig. 6, and *Mem. Geol. Sur.*, *Felsitic Lavas* (1885) pl. ii, figs. 1, 2; Teall, *Brit. Petr.* pl. xxxviii.

[9] *Q. J. G. S.* (1901) lvii, 31–37, pl. i.

[10] *Ibid.* (1891) xlvii, 518–519.

[11] Reed, *ibid.* (1899) lv, 763–766.

The common soda-rhyolites (sometimes called by the loosely defined name 'ceratophyre' or 'quartz-ceratophyre') cannot always be recognized as such without the aid of chemical analysis. Of very distinctive types, however, are those acid lavas in which the ferro-magnesian mineral is of a soda-bearing variety. The best examples come from the island of Pantelleria[1], S.W. of Sicily. They show phenocrysts of anorthoclase, deep brown pleochroic cossyrite, and green ægirine-augite. In the vitreous type of *pantellerite* cossyrite is much more abundant than the pyroxene, and the ground-mass is mainly of brownish glass enclosing little crystals of the same minerals. In another type (ægirine-pantellerite of Washington) the ground-mass has a strong flow-structure, and is crowded with microlites of ægirine set in a very finely crystalline quartzo-felspathic matrix. The *comendite* of Pantelleria is a paler rock, having a ground-mass chiefly of idiomorphic felspars with interstitial quartz and some small irregular crystals of the coloured silicates. Rhyolites with riebeckite have been described from British East Africa[2].

[1] Washington, *Journ. Geol.* (1913) xxi, 695–708.
[2] Prior, *Min. Mag.* (1903) xiii, 242–244.

CHAPTER XIII

TRACHYTES

The trachytes are lavas which, with a lower percentage of silica than the rhyolites, have as much or more of the alkalies. The typical *trachytes* consist essentially of alkali-felspars with a relatively small amount of coloured minerals and without quartz. The name trachyte (given by Haüy to denote the rough aspect of the rocks in hand-specimens) is used in the older literature to cover all the more acid half of the volcanic rocks. From it have been separated off, on the one hand, the rhyolites of modern nomenclature and, on the other, some hornblende- and mica-andesites, *etc.* A distinction can often be made between *potash-trachytes* and *soda-trachytes*, according to the nature of the dominant felspathic mineral.

We shall also include in this chapter certain less common types in which the alkali-felspar is accompanied by labradorite, while a greater abundance of the ferro-magnesian silicates gives the rocks a darker and denser character. These *vulsinites* and *ciminites* make transitions from the trachytes to the andesites and basalts.

Constituent minerals. Felspars rich in potash or soda are by far the most abundant minerals in the rocks here considered. They occur both as phenocrysts and as the chief element in the ground-mass. The most prominent is usually orthoclase of the *sanidine* variety, often showing a rough ortho-pinacoidal cleavage. In phenocrysts it has either a tabular or a columnar habit, and both may occur in the same rock. Carlsbad-twinning is frequent, and in the larger crystals may show the broken divisional line due to interpenetration. Some degree of zonary banding is occasionally found. The plagioclase common in potash-trachytes is usually *oligoclase*, but in the vulsinites a more basic variety, while *albite* occurs in the more

distinctively sodic trachytes. The phenocrysts often show Carlsbad- as well as albite-twinning; zonary banding is not uncommon; and parallel intergrowth with sanidine may be noted. Anorthoclase is probably an intergrowth on a more minute scale. In some trachytes the presence of *sodalite* marks affinity with the more alkaline family of the phonolites.

In the true trachytes the most common ferro-magnesian element is perhaps brown *biotite*, in hexagonal flakes almost always affected by corrosion by the enclosing magma ('resorption'). This is shown by a certain degree of rounding and the formation of a dark or opaque border, or even the total destruction of the flake, the resulting products being especially magnetite and sometimes greenish augite in minute granules (fig. 54, *A*). The frequent preservation of the original crystal-forms proves that the process is not one of fusion and recrystallization, but rather pseudomorphism depending on changed physical conditions and chemical reactions with the fluid magma. Brown *hornblende* is a less frequent constituent, in idiomorphic crystals with similar resorption-phenomena. The *augite*, which is scarcely less common than biotite as a constituent of trachytes, never shows this feature. It is usually pale green in thin slices. Unlike biotite and hornblende, it often occurs in a second generation as a constituent of the ground-mass. The rhombic pyroxene of certain trachytes is of a deeply coloured and vividly pleochroic variety (*hypersthene* or *amblystegite*), giving red-brown, yellow-brown, and green colours for the several principal directions of absorption.

Olivine is a constituent of certain types of trachyte, as well as of the more basic ciminite. Iron-ores (*magnetite*) occur but sparingly in these rocks. Yellowish *sphene* in good crystals is highly characteristic; and *apatite* is common in colourless needles or sometimes in rather stouter prisms with violet dichroism. The trachytes often contain a little *zircon* in minute prisms.

Among less common minerals may be mentioned the *tridymite* of certain trachytes, in aggregates of minute flakes with very weak refringence and birefringence. As secondary products in trachytic (as also in andesitic) rocks, *opal* and other

forms of soluble silica are not uncommon. Normally isotropic, these substances sometimes show double refraction as a consequence of strain, usually about centres, so as to imitate a spherulitic structure. Opal sometimes encloses little flakes or aggregates of tridymite, or is coloured red by included scales of hæmatite. It occurs in the form of veins and irregular knots or patches.

Ground-mass. In contrast with the rhyolites, the rocks under consideration have few glassy representatives, and the ground-mass is commonly holocrystalline, or at least with no sensible amount of glassy residue. This is especially true of the typical trachytes. Fluxional phenomena are common, but the characteristic banding of the rhyolites is here wanting. Vesicular structure is rare, and perlitic cracks are not found; but, in consequence of the crystalline nature of the ground, with a tendency to idiomorphism in its elements, a miarolitic or drusy structure may be met with. Any structure comparable with the spherulitic is rare, though a rough radial grouping of felspar prisms is sometimes observable.

Non-felspathic constituents play in most cases a small part in the ground-mass of the rock here considered. The ground consists, in the trachytes proper, essentially of minute felspars, which may, however, vary somewhat in habit. Most commonly they are 'lath-shaped' microlites, with some degree of parallel disposition in consequence of flow, and this type of ground is so characteristic of these rocks that it is often styled the *trachytic*. On the other hand the felspars may have a shorter and stouter shape, recalling some of the rocks grouped above under the porphyries, and this structure is accordingly designated the *orthophyric*.

In some volcanic districts, such as that of the Laacher See, near the Rhine, occur trachytic rocks in which the ground-mass is reduced to very small amount (fig. 53, *C*); and there are some in which ground-mass is wholly wanting. Such rocks, composed principally of rather coarsely crystalline sanidine, and known as 'sanidinites,' are found as blocks in volcanic tuffs.

Leading types. The *domites* of Auvergne are biotite-trachytes having an exceptionally high silica-percentage, due to the presence of tridymite. This mineral occurs in clusters of minute scales, and is probably of solfataric origin. In other trachytes from the same district the ferro-magnesian mineral

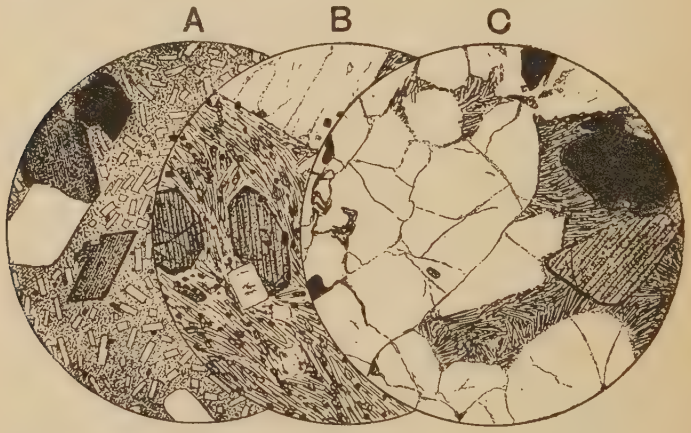

FIG. 53. TRACHYTES; ×20.

A. Hornblende-Trachyte, Grand Sarcoui, Auvergne. Phenocrysts of brown hornblende, magnetite, and oligoclase: ground-mass micro-porphyritic, with little felspar crystals.

B. Augite-Trachyte, Solfatara, Naples. Phenocrysts of pale green augite, sanidine, and some oligoclase: felspathic ground-mass with flow-structure, and enclosing scattered granules of augite and magnetite.

C. Augite-Trachyte or Sanidinite, Laacher See, Eifel. Mainly of clear sanidine, with some oligoclase, augite, magnetite, apatite, and sphene (not shown): the ground-mass reduced to scattered interstitial patches.

is either biotite or hornblende (fig. 53, *A*). Another well-known rock is that of Drachenfels, on the Rhine (fig. 54, *A*). It is a *biotite-trachyte*, with phenocrysts of sanidine and smaller ones of oligoclase. The fluxional trachytic ground-mass is essentially of orthoclase but contains a small quantity of interstitial quartz.

Biotite-trachytes of various ages are known in Britain. A Tertiary example from the northern border of the Cuillin Hills[1] is a non-porphyritic rock, showing partly resorbed flakes of biotite and minute octahedra of magnetite in a trachytic ground-mass with secondary epidote. Others from Ben Hiant in Ardnamurchan contain phenocrysts of orthoclase and anorthoclase, and a violet pleochroic apatite is sometimes abundant. More interesting are the highly potassic rocks which occur as lavas in the New Red Sandstone of the Exeter district[2]. One type is a biotite-trachyte rather rich in mica and approximating in characters to a minette (Killerton); another is an olivine-biotite-trachyte (Knowle); and the most frequent varieties represent a transition from this type to an orthoclase-bearing basalt (Pocombe, *etc.*).

Good examples of *olivine-trachyte* are found in the Carboniferous about Campbelltown, Kintyre. These are of more sodic composition, and contain phenocrysts of albite and oligoclase as well as orthoclase. The olivine is represented by serpentinous pseudomorphs with a deep border of iron-oxide, and there is little indication of any other ferro-magnesian mineral.

Soda-trachytes, sometimes styled 'ceratophyres,' are represented among the British Ordovician lavas. One occurs at Hamilton Hill, in Peeblesshire[3]. Others, with phenocrysts of albite, have been described from Skomer Island, Pembrokeshire[4]. Pseudomorphs after olivine and hypersthene characterize different types, and there are also rocks containing little or no ferro-magnesian elements.

The Scottish Carboniferous *augite-trachytes*[5] are also rather rich in soda. They occur both as lava-flows and as minor intrusions, graduating into the orthophyres already mentioned (p. 113). Good examples are found in the neighbourhood of Haddington. They consist of alkali-felspars with more or less

[1] *Tertiary Igneous Rocks of Skye* (*Mem. Geol. Sur.* 1904) 58.
[2] Teall, *Geology of Exeter* (*Mem. Geol. Sur.* 1902) 76–85.
[3] Teall, *Ann. Rep. Geol. Sur.* for 1896, 40.
[4] Thomas, *Q. J. G. S.* (1911) lxvii, 190–193; *Geology of Country around Milford* (*Mem. Geol. Sur.* 1916) 31–33.
[5] Hatch, *Tr. Roy. Soc. Edin.* (1892) xxxvii, 115–126, pl. i, ii; Bailey, *Geology of E. Lothian* (*Mem. Geol. Sur. Scot.* 1910) 127–133.

of a bright to pale green pleochroic augite, doubtless a soda-bearing variety, and contain phenocrysts of sanidine, sometimes with intergrowths of oligoclase, in a holocrystalline ground-mass. The latter is chiefly of sanidine prisms, with a minor proportion of striated felspar. Augite builds imperfect crystals and grains and numerous smaller granules; magnetite occurs sparingly in the same manner; and occasional needles of

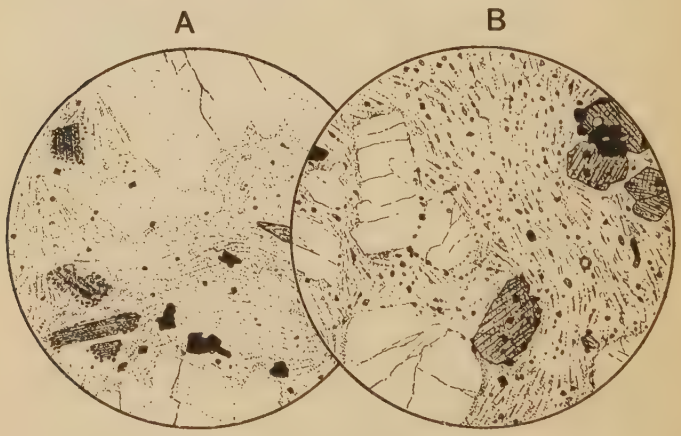

FIG. 54. TRACHYTES; ×20.

A. Biotite-Trachyte, Drachenfels, Siebengebirge, Rhine. Phenocrysts of oligoclase and sanidine, with magnetite and much-resorbed biotite, in a fine-textured trachytic ground-mass.

B. Augite-Trachyte, Peppercraig, Haddington. Phenocrysts of sanidine, pale green soda-augite, and magnetite: ground-mass showing flow-structure.

apatite are seen (fig. 54, *B*). Some varieties have a little interstitial quartz (Dirleton). A quartz-bearing trachyte is found also in the Melrose district, besides augite-olivine-trachyte and *riebeckite-trachyte*[1].

Certain of these Carboniferous trachytes contain a little analcime, and may possibly have had some nepheline. Such

[1] Lady McRobert, *Q. J. G. S.* (1914) lxx, 303–314.

rocks are distinguished as *phonolitic trachytes*, and in other types the coming in of sodalite has the same significance. A considerable diversity of augite-trachytes is found in the neighbourhood of Naples (fig. 53, *B*), and *sodalite trachytes* are represented there. The trachytes of the Laacher See, and especially the *sanidinites*, are often rich in sodalite, usually colourless, moulded on the felspar. Exceptionally it is idiomorphic and has the noscan type of inclusions. The coloured silicate here is a brown hornblende (fig. 53, *C*); sphene is abundant, and a spinel (hercynite) is sometimes present.

Washington[1] has proposed the name *vulsinite* for a group of rocks intermediate between trachyte and andesite. They contain a considerable amount of a basic plagioclase in addition to the alkali felspar, and the ferro-magnesian constituent is typically augite. In examples from Bolsena in Italy the phenocrysts are of alkali felspar, anorthite, augite, and biotite, and the ground mass is of soda orthoclase, augite, *etc.*, with trachytic structure. One from the Viterbo district has labradorite in place of anorthite. A somewhat more basic type, from the Mti Cimini in the latter district, is styled *ciminite*[2]. It has the same association of sanidine with a basic felspar, but carries phenocrysts of olivine, as well as of augite and felspar. A well-known example of this is the 'Arso trachyte,' the Ischia lava of A.D. 1302, which approximates in some features to the basalts. The ground mass is of felspar microlites with interstitial glass, and is sometimes vesicular.

[1] *Journ. Geol.* (1896) iv, 547–554, 833.
[2] *Ibid.* (1896) iv, 834–838, and (1897) v, 354.

CHAPTER XIV

PHONOLITES AND LEUCITOPHYRES

The phonolites and their allies differ chemically from the trachytes by a greater richness in alkalies, which expresses itself mineralogically in the presence of various felspathoid minerals in addition to the alkali-felspars. These rocks are therefore the volcanic equivalents of the nepheline-syenites, just as the trachytes are of the syenites proper. The name *phonolite* (a translation of 'clinkstone,' from the supposed sonorous quality of the rock when struck) seems to have been in general use before the presence of microscopic nepheline in the rock was demonstrated, giving a character of precision to the definition. Phonolites are often distinguished as the '*trachytoid*,' which are poor in nepheline and do not differ greatly from trachytes, and the more typical '*nephelinitoid*' phonolites, containing nepheline in abundance. The original *leucitophyres* (of Coquand) were apparently any rocks with conspicuous crystals of leucite, but the name is now generally restricted to the types containing an alkali-felspar (sanidine) as an essential constituent. The leucitophyres are a group of extremely restricted distribution, and the unstable nature of the characteristic mineral must make such rocks difficult to detect among the older lavas, a remark applicable also in some degree to the phonolites.

Constituent minerals. The felspathic element is almost exclusively orthoclase (*sanidine*) with the same characters as that of the trachytes. An *anorthoclase* is recorded as phenocrysts in some phonolites, but albite is very rare, as well as all lime-bearing felspars.

The *nepheline* which is the distinctive mineral of the phonolites, and occurs in many leucitophyres, shows a very different habit from that usual in the plutonic rocks. It occurs only in minute crystals in the ground-mass, having the form of a short hexagonal prism with basal planes, and giving squarish

or hexagonal sections (fig. 55, *B*). Owing to the small size of the crystals and the optical properties of the mineral, it is liable to be overlooked. Its decomposition gives rise to various soda-zeolites, which occur in nests and veins in many phonolites. The *leucite* of the leucitophyres is always idiomorphic, giving characteristic octagonal and rounded sections (fig. 57, *B*). Twin-lamellation is very frequent in the phenocrysts, but the smaller crystals often behave almost as if isotropic. The leucite may enclose needles of augite and crystals of the earlier-formed minerals, but not of felspar. Minerals of the sodalite group are found very frequently, almost always in idiomorphic dodecahedra. The *sodalite* is clear when fresh, but often turbid from alteration: zonary structure is frequent. The blue *haüyne* is less often met with, but *nosean* may be very plentiful, usually forming crystals of some size, and always showing more or less plainly its characteristic structure and border[1] (figs. 56, 57, *B*). The sodalite-minerals give rise by alteration to natrolite and other zeolites.

The most usual ferro-magnesian silicate is *ægirine*, easily recognized by its bright green colour, characteristic pleochroism, and low extinction-angle in vertical sections. If a pale augite occurs, it has a border of more pronounced green colour. Amphiboles are less frequently present. They include especially the deep red-brown *barkevicite*, but sometimes the blue soda-hornblendes and more rarely the very deep brown triclinic cossyrite. A magmatic replacement of hornblende by ægirine can sometimes be verified (fig. 55, *B*). Biotite is rare, and suffers much from resorption.

Primary *iron-ores* are never abundant, but, as in the trachytes, there is sometimes finely divided magnetite arising from the magmatic alteration of silicate minerals. Other accessory minerals are *sphene* and *apatite* (colourless or blue). More special constituents are *olivine*, found in a few phonolites, and *melanite*, occurring both in phonolites and in leucitophyres.

Ground-mass and structures. The rocks of this family are normally holocrystalline. The *phonolites* are constantly

[1] Teall, *Brit. Petr.* pl. XLI, fig. 1, and XLVII, fig. 4.

porphyritic, sanidine and ægirine being the chief phenocrysts. The same minerals in a second generation, together with nepheline, make up the ground-mass, and the structure of this varies with the relative proportions of the several constituents. A strong preponderance of felspar, in closely packed slender crystals, reproduces the appearance of the common types of trachytes (fig. 55, *A*); while richness in nepheline and ægirine

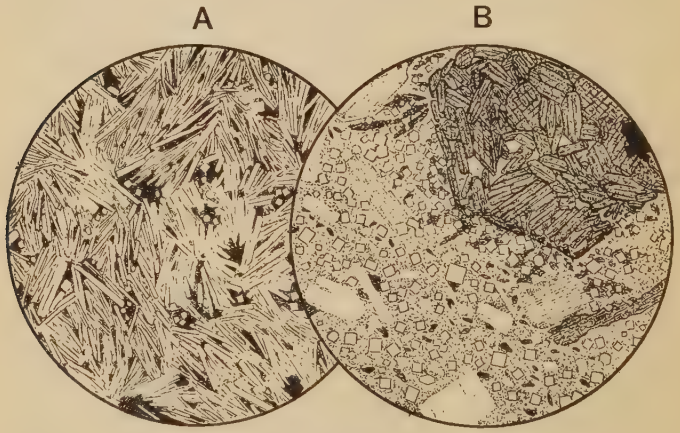

FIG. 55. PHONOLITES; ×20.

A. Trachytoid Phonolite, Dunedin, New Zealand. Chiefly of sanidine in tabular crystals with interstitial ægirine and a few small crystals of nepheline.

B. Phonolite rich in nepheline, Brüx, Bohemia. A large hornblende phenocryst has been transformed by magmatic reactions to an aggregate of green ægirine.

gives rise to other structures. The ægirine of the ground-mass is sometimes in little columnar crystals, varying in size down to mere microlites (fig. 56), sometimes in ophitic patches enclosing the nepheline and enwrapping the felspar (fig. 55, *A*).

Some types of *leucitophyre* are conspicuously porphyritic, leucite, as well as sanidine and ægirine, occurring in two generations with very different dimensions. In other types it is not

easy to make any distinction between phenocrysts and groundmass, and sometimes the rock as a whole shows a relatively coarse texture. A special structure is seen when leucite is surrounded by a border of ægirine crystals, usually with tangential arrangement.

Leading types. Rocks of this family are barely represented in Britain. Some of the Carboniferous trachytic rocks of Scotland contain nepheline, or analcime supposed to replace nepheline, but usually in very small amount. One example, from Fintry, near Lennoxtown, Stirlingshire[1], is a typical *trachytoid phonolite*. It is a non-porphyritic rock composed principally of tabular crystals of sanidine with bright green ægirine and paler ægirine-augite. Nepheline, in the usual small idiomorphic crystals, is distributed sparingly and unevenly, but is easily recognized where it is enclosed in the pyroxene. Trachytoid phonolites occur in Auvergne, Bohemia, Saxony, New Zealand (fig. 55, *A*), and other countries. They include porphyritic varieties with phenocrysts of sanidine and ægirine. From the Dunedin district, N.Z., Marshall[2] has described an 'andesitic phonolite,' which encloses phenocrysts of oligoclase; and further transitions towards the andesite family are represented by the 'latite-phonolites' of Lindgren and Ransome (Cripple Creek, Colo.).

The more normal *phonolites*, rich in nepheline, have a wider distribution, though nowhere comparable in importance with such rocks as rhyolites or basalts. The common porphyritic elements are sanidine and ægirine: nepheline phenocrysts are rarely found (British East Africa[3]). Typical phonolites occur in Bohemia (fig. 55, *B*). Some from the neighbourhood of Aussig are rich in secondary zeolites, including natrolite in radiate fibrous growths which show the black cross between crossed nicols. In America good examples occur in the Black Hills of Dakota[4] (fig. 57, *A*) and the Cripple Creek district, Colorado[5].

[1] *Geology of Glasgow* (*Mem. Geol. Sur. Scot.* 1911) 144.
[2] *Q. J. G. S.* (1906) lxii, 401–402.
[3] Prior, *Min. Mag.* (1903) xiii, 237–239.
[4] Cross, *Bull.* 150 *U. S. Geol. Sur.* (1898) 191–193.
[5] Cross, 16*th Ann. Rep. U. S. Geol. Sur.* (1895) 25–43; Lindgren and Ransome, *Pro . Paper* 54 *U. S. Geol. Sur.* (1906) 57–67, pl. VII.

Although *hornblende-phonolites* are of rare occurrence, it is certain that hornblende has been a very common mineral, and has been replaced by ægirine as the result of magmatic reactions. Rocks from the Cape Verd Islands[1] show idiomorphic phenocrysts of brown hornblende changed only on their borders and others completely replaced by aggregates of ægirine crystals (compare fig. 55, *B*). Of different significance is the occurrence of brown and blue soda-amphiboles (cossyrite, arfvedsonite,

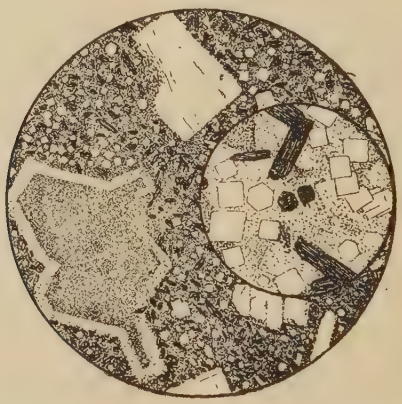

FIG. 56. NOSEAN-PHONOLITE, WOLF ROCK, CORNWALL; ×20.

Showing phenocrysts of sanidine and a large crystal-group of nosean, turbid in the interior, in a ground-mass of sanidine, nepheline, and ægirine. These last two minerals are more clearly shown in the small inset circle, ×100.

riebeckite, *etc.*) in addition to the usual pyroxene. This is found in phonolites from the Apache Mts (Texas), Cripple Creek (Colo.), British East Africa, and the Dunedin district (N.Z.).

A sodalite mineral, usually with the characters of nosean, is not uncommon, and sometimes becomes so prominent as to warrant the name *nosean-phonolite*. Here belongs our only typical British phonolite, that of the Wolf Rock, off the Land's

[1] Harker, *G. M.* 1907, 105–106.

End of Cornwall[1]. It contains abundant phenocrysts of nosean and sanidine, with a few of ægirine, in a ground-mass of sanidine and nepheline enclosing numerous dirty green microlites of ægirine (fig. 56).

Another distinctive type is a *melanite-phonolite*. The deep brown garnet occurs as idiomorphic phenocrysts, often showing zonary growth. Examples are found in the Cape Verd Islands and the Kaiserstuhl district of Baden.

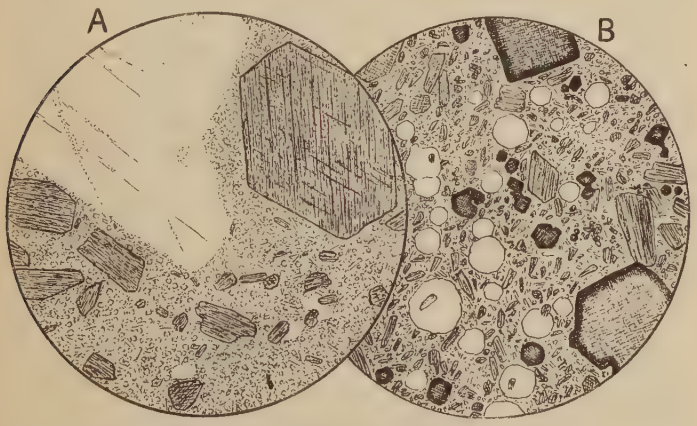

Fig. 57; ×20.

A. Phonolite, Black Hills, S. Dakota. Phenocrysts of soda-sanidine and ægirine in a ground-mass of nepheline and sanidine.

B. Leucitophyre, Burgberg, near Rieden, Eifel. Phenocrysts of green ægirine-augite, dark-bordered nosean, and clear leucite in a ground-mass of ægirine-augite, nepheline, and sanidine.

Glassy phonolites, including phonolite-obsidian, are exceptional, but are known in Tenerife and British East Africa. Here the distinctive mineral nepheline is not developed, but the pale glassy matrix encloses microlites of sanidine and ægirine. Another vitreous type is the *kenyte* of Mt Kenya[2] and

[1] Allport, *G. M.* 1871, 247–250, and 1874, 462–463; Teall, *Brit. Petr.* 367–368, pl. xli, fig. 1.

[2] Gregory, *Q. J. G. S.* (1900) lvi, 211–214.

British East Africa[1]. Here the felspar is anorthoclase in large porphyritic crystals, and the other phenocrysts are a pale green augite and abundant olivine.

The *leucitophyres* are a very small group of rocks, known only from a few districts, and best developed in the late Tertiary lavas of the Eifel. The leucite is often of two generations, the larger crystals being frequently of irregular shape. It is always accompanied by nosean and sanidine (fig. 57, *B*). The ferro-magnesian mineral is a green pleochroic augite with zonary banding: the other constituents are sphene, occasionally biotite, and often a little melanite. The structure of the rocks is very variable. In some there is a well-defined ground-mass of minute nepheline, sanidine, augite, and leucite, enclosing phenocrysts of leucite and nosean (Olbrück, *etc.*). In other varieties there is but little sanidine (Schorenberg), while others again have sanidine in large shapeless plates enclosing the other constituents instead of a ground-mass (Perlerkopf). Leucitophyres showing some variety of characters occur at several volcanic centres in Italy[2]. They often contain resorbed flakes of biotite.

Here too should be mentioned a peculiar leucite-sanidine-rock (Orenda type) from the Leucite Hills of Wyoming[3]. It is a fine-textured rock composed of little prisms of sanidine and crowds of minute leucite crystals with a smaller amount of ferro-magnesian minerals. These include a pale mica (phlogopite), in addition to resorbed biotite, microlites of augite, and sometimes a peculiar yellow amphibole.

[1] Prior, *Min. Mag.* (1903) xiii, 246–248.

[2] Washington, *Journ. Geol.* (1896) iv, 559–561 (Bolsena), 840–845 (Viterbo); (1897) v, 43 (L. Bracciano), and 248-249 (Rocca Monfina).

[3] Cross, *Amer. J. Sci.* (1897) iv, 123–126; *Bull.* 150 *U. S. Geol. Sur.* (1898) 186–191.

CHAPTER XV

ANDESITES

In this family we include all the lavas of 'intermediate' composition not embraced in the preceding chapters. The name andesite, first used by von Buch and derived from the prevalence of such rocks in the Andes, is roughly equivalent to Abich's 'trachydolerite,' implying the intermediate position of these lavas between the acid ones (trachytes of older writers) and the basic (dolerites). The characteristic minerals are a soda-lime-felspar and one or more ferro-magnesian minerals. The alkali-felspars and quartz of the acid rocks are typically absent, as are also the lime-felspar and olivine of the basic rocks. The andesites are distinguished, according to the dominant ferro-magnesian constituent, as *hornblende-*, *mica-*, *augite-*, and *hypersthene-andesites*. Further there is usually recognized a quartz-bearing and more acid division, known as *dacites* or quartz-andesites.

Those petrologists who restrict the name andesite to rocks of late geological age, apply to their pre-Tertiary equivalents the name 'porphyrite[1].' Under the same title they include various rocks of hypabyssal types, and it is to these latter that we have already confined the name. Again, certain English petrologists have used the name 'porphyrite' for andesites which have undergone some degree of change by weathering, *etc.*, a distinction which seems scarcely important enough to be recognized in classification or nomenclature.

As regards the general affinities of the family, the dacites have features in common with the rhyolites, the hornblende- and mica-andesites with the trachytes, and the pyroxene-andesites with the basalts, marking thus the intermediate position held among the volcanic rocks by the lavas here considered. As regards the appropriateness of the name, it is

[1] Many also of the rocks designated 'melaphyre' are pyroxene-andesites, others being basalts.

remarkable that the lavas of the great volcanic belt of the Andes belong, in so far as they are known, almost exclusively to this family.

Phenocrysts. Soda-lime-felspars are the most abundant elements porphyritically developed in these rocks. They include members varying from oligoclase to anorthite, but *andesine* and *labradorite* are the most common. As a rule, the more acid plagioclase belongs to the hornblende- and mica-andesites and dacites, the more basic to the pyroxene-andesites[1]. The crystals, however, are often strongly zoned (fig. 60, *A*), showing a change from a more basic variety in the centre to a more acid at the margin. They are idiomorphic and of tabular habit. With albite-lamellation is frequently associated twinning on the pericline or on the Carlsbad law. The commonest inclusions are glass-cavities, either as 'negative crystals' or rounded: sometimes large irregular cavities occupy much of the bulk of a crystal.

The *hornblende* of andesites is in idiomorphic prisms, often twinned. It is usually a brown pleochroic variety with low extinction-angle, but green hornblende also occurs. The mica is a brown strongly pleochroic *biotite* with extinction sometimes sufficiently oblique to show lamellar twinning parallel to the base. Both hornblende and biotite show the same resorption-phenomena as in the trachytes. It is probable that some part of the finely divided magnetite and granular augite in the ground-mass of certain andesites comes from the breaking up of hornblende altered in this way[2]. By decomposition of the ordinary kind the hornblende and mica of andesites give rise to chlorite, magnetite, carbonates, *etc.*

The *augite* is in well-shaped crystals, light green and usually without sensible pleochroism. Twin-lamellation is common. Alteration may give rise to chlorite, epidote, calcite, *etc.* The rhombic pyroxene in the andesites is often *hypersthene*, or at least a distinctly coloured and more or less pleochroic variety.

[1] French petrologists recognize 'andesites' and 'labradorites' as distinct groups, characterized by andesine and labrador-felspar respectively; but this is with reference to the ground-mass.

[2] Washington, *Journ. Geol.* (1896) iv, 273–278.

It builds idiomorphic crystals, in which the pinacoid faces are more developed than the prism; so that the cross-section is a square with truncated corners, as contrasted with the regular octagon of augite. In longitudinal sections the straight extinction is of course characteristic. The rhombic pyroxene is often converted in the older rocks to bastite.

The *quartz* of the dacites is either in good hexagonal pyramids or more or less rounded and corroded, with inlets of the ground-mass.

Original iron-ores are usually not abundant: *magnetite* is the only one commonly found. Needles of *apatite* occur, and in the more acid andesites little *zircons*. Some of the more basic rocks have sparingly phenocrysts of *olivine*. As occasional accessories may be noted *tridymite* (in druses), *garnet*, and *cordierite*.

Structure of ground-mass. In many andesites the only mineral which occurs distinctly in two generations is felspar. The felspar of the ground-mass builds little 'lath-shaped' crystals, often simple, sometimes twinned, but usually without repetition. It is probably, as a rule, of a more acid variety than the phenocrysts, labradorite, andesine or oligoclase occurring in different cases. Augite also may be present as a constituent of the ground-mass, forming very small crystals of pale green tint.

Some of the hornblende- and mica-andesites have a *trachytic* type of ground-mass, composed essentially of very small felspar-laths with little or no glassy base, as in the typical trachytes. It is not always easy to ascertain whether any glass is present or not. From this type, as from the others, there are, however, transitions to rocks with a ground-mass mainly glassy.

Less common is a '*microfelsitic*' or cryptocrystalline structure. This is seen in many of the dacites. In some cases spherulitic structures are found (*cf.* fig. 59, *A*).

In most typical andesites, and especially in the pyroxene-bearing kinds, the ground-mass has the very distinctive 'felted' character termed by Rosenbusch *hyalopilitic*. This

consists of innumerable small felspar-laths, simple or once twinned, often with evident flow-structure, and a residuum of glassy matter. So characteristic is this type, that it is often spoken of as the 'andesitic' ground-mass. When the little felspars are closely packed together, to the exclusion of any glassy base, we have the *pilotaxitic* structure of Rosenbusch. On the other hand, by increase in the proportion of isotropic

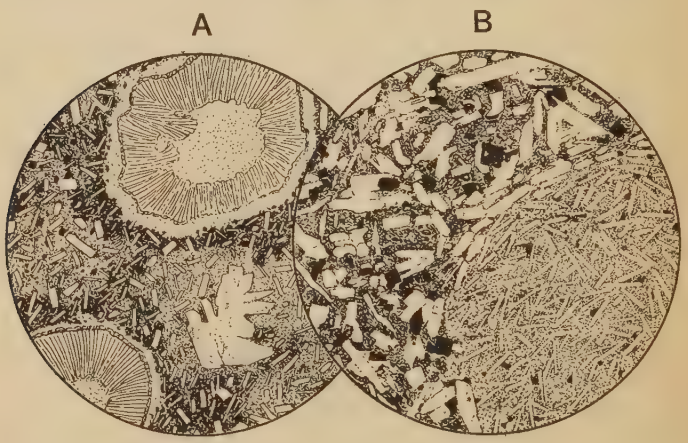

FIG. 58. VESICULAR AUGITE-ANDESITES; ×20.

A. Stockdale, Westmorland: showing amygdaloidal structure; vesicles occupied chiefly by a pale green chlorite.

B. Papadil, Isle of Rum: showing part of a large vesicle filled by the oozing in of the residual magma, now represented mainly by felspar crystallites with some magnetite.

base, these andesites graduate into more or less perfectly *glassy* forms. Wholly glassy types (andesite-obsidian, including andesite-pumice) are known in small development only, except in so far as they form part of tuffs.

Vesicles are common, and their infilling by secondary products gives rise to amygdales (fig. 58, *A*). In other cases the final residual magma has broken into the vesicles, which

thus become occupied by glass or by material showing a lower grade of crystallization than the mass of the rock (fig. 58, *B*).

Leading types. Of *dacites*[1] examples occur among the Old Red Sandstone lavas of Scotland, and several have been noticed in the eastern part of Fife. That described by Prof. Judd[2] from Scroggieside is perhaps rather on the border-line between rhyolite and dacite. It has a glassy modification, which the author styles mica-dacite-glass. Phenocrysts of oligoclase and deep brown biotite are embedded in a glassy ground-mass containing trichites, globulites, and imperfect microlites of felspar (perhaps orthoclase). The glass shows beautiful perlitic fissures. Other dacites are recorded from Leuchars and Wormit Bay in the same district[3]. Little is known of true dacites among the Lower Palæozoic lavas of this country, though some of the rocks included above as rhyolites would probably be styled dacites by certain petrologists. The name has also, as remarked above, been applied loosely to some of the acid hypabyssal rocks.

A number of dacites were described from Nevada by Zirkel[4], and some of Richthofen's 'glassy rhyolites' from the same region seem to belong rather to this family[5]. Dacites are also well represented among the Tertiary and Recent lavas in California, Oregon, and Washington. Biotite is prominent among the ferro-magnesian minerals, and sometimes hornblende. At Lassen's Peak in California[6] occurs a type rich in phenocrysts, which consist of plagioclase felspar, biotite, hornblende, and quartz, while the ground-mass is essentially of glass (fig. 59, *A*). In New Zealand, in the Hauraki gold-bearing

[1] The name was first used by Stache for quartz-bearing andesites in Transylvania (Dacia).

[2] *Q. J. G. S.* (1886) xlii, 427–429, pl. xiii, figs. 7, 8.

[3] Flett, *Geol. E. Fife* (*Mem. Geol. Sur. Scot.* 1902) 387.

[4] *Micro. Petrogr. Fortieth Parallel* (1876) 134–142: see also Iddings, *Monog.* xx *U. S. Geol. Sur.* (1893) 368–373 (Eureka district), and *Bull.* 150 *U. S. Geol. Sur.* (1898) 215–217.

[5] Hague and Iddings, *Amer. J. Sci.* (1884) xxvii, 460–461.

[6] Diller, *ibid.* (1883) xxvi, 231–233, and *Bull.* 150 *U. S. Geol. Sur.* (1898) 217–219.

region of the North Island, Prof. Sollas[1] has described and figured dacites, in which hornblende is the ferro-magnesian mineral. Quartz occurs sometimes in corroded grains, as well as in the ground-mass.

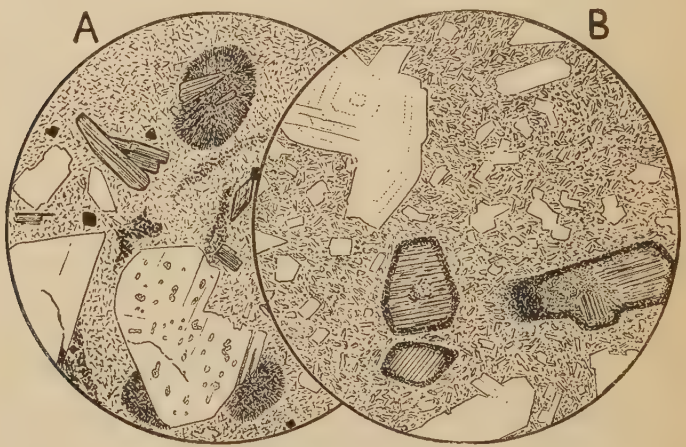

FIG. 59. ANDESITIC LAVAS, CALIFORNIA; ×22.

A. Dacite, Lassen's Peak. The phenocrysts are of andesine (some with large glass-inclusions), hornblende, biotite, and magnetite. In parts of the slide, not figured, quartz, sanidine, and pyroxene occur more sparingly. The ground-mass is a clear glass crowded with little acicular crystallites. There are also growths analogous to spherulites, but with only very imperfectly radiate structure.

B. Hornblende-Andesite, Mt Shasta. The phenocrysts are of hornblende (with resorption-border) and zoned labradorite. The ground-mass consists of little microlites, chiefly of andesine.

The hornblende- and mica-andesites include among other types some with alkaline affinities, which may be termed *trachytic andesites*. Typical examples are found in the Siebengebirge, on the Rhine (fig. 60, *B*). The phenocrysts are of labradorite, brown hornblende and biotite, both affected by

[1] *Rocks of Cape Colville Peninsula*, vol. i (1905) 138–147, 164, 197, 201, with full-page plates.

magmatic resorption, and often pale green augite. The ground-mass has the trachytic structure, and consists of oligoclase with some orthoclase.

Few *hornblende-andesites* are known in the British Isles. One good example occurs on the summit of Beinn Nevis[1], and, though of Palæozoic age, it is fairly fresh. The phenocrysts are of light brown idiomorphic hornblende and a plagioclase full of glass-inclusions, *etc.* The ground-mass is obscured by specks of iron-ore and alteration-products, but is seen to consist largely of densely packed, minute felspar-microlites. Hornblende-andesites are found in Glencoe, but mostly in a considerably altered state. In particular, they show a development of the red manganese-epidote (withamite) which is seen in the well known 'porfido rosso antico' from Egypt. An andesite with pseudomorphs after hornblende occurs, together with augite-andesites, in the Ordovician volcanic group at Llangynog, near Caermarthen[2]. Again, an Ordovician hornblende-andesite of somewhat basic composition occurs near Kildare[3], and others, brecciated and altered, are found on Slieve Gallion, Co. Londonderry[4].

A simple mica-andesite is a rare type, but hornblende-andesites, often with biotite in addition and frequently containing some pyroxene, have a wide distribution. Good examples are abundant among the Tertiary lavas of the Western States of America (fig. 59, *B*). The 'trachytes' of Zirkel[5] and others, in the Great Basin and elsewhere, are in part hornblende-mica-andesites[6].

Andesites having a pyroxene as their dominant non-felspathic constituent are perhaps more widely distributed than any other group of lavas, and are largely represented among the products of volcanoes now active. Since a rhombic and a monoclinic pyroxene are often associated, the rocks are spoken of as *pyroxene-andesites*, while the marked predominance of

[1] Teall, *Brit. Petr.* pl. xxxvii, fig. 1.
[2] Cantrill and Thomas, *Q. J. G. S.* (1906) lxii, 243.
[3] Reynolds and Gardiner, *Q. J. G. S.* (1896) lii, 602.
[4] Cole, *Sci. Tr. Roy. Dubl. Soc.* (1897) vi, 222, *etc.*
[5] *Micro. Petrogr. Fortieth Parallel* (1876) 143–162.
[6] Hague and Iddings, *Amer. J. Sci.* (1883) xxvi, 460

one or other of these minerals gives a hypersthene- or an augite-andesite.

The Old Red Sandstone lavas of Scotland are mostly pyroxene-andesites, ranging from a relatively acid type (dacite) to varieties verging on basalt. Some of the former, from North-East Fife, have already been mentioned. In the same district are good examples of more basic types also (Northfield

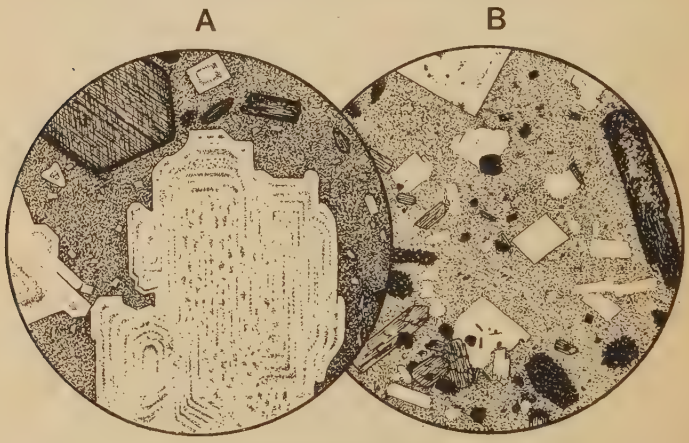

FIG. 60. HORNBLENDE-ANDESITES; ×20.

A. Altsohl, Hungary: showing phenocrysts of zoned andesine and brown hornblende (with marginal resorption-effect) in a fine-textured ground-mass.

B. Stenzelberg, Siebengebirge, a trachytic andesite: destruction of the hornblende is almost complete, and there are idiomorphic crystals of pale augite.

and Causeway Head)[1]. From Dumyat and elsewhere in the Ochils[2] come typical pyroxene-andesites with both hypersthene and augite, the former predominating. The freshest type has an unaltered glassy base, which in other varieties is devitrified.

[1] Judd, *Q. J. G. S.* (1886) xlii, 425–427, pl. XIII, figs. 1, 2: see also Flett, *Geol. E. Fife* (*Mem. Geol. Sur. Scot.* 1902) 386–387.

[2] Flett, *Tr. Edin. G. S.* (1897) vii, 290–297, pl. XVII; Watts in Geikie's *Ancient Volcanoes* (1897) i, 274–276.

More basic varieties about Taynuilt, in Argyllshire, contain a variable amount of olivine[1]. The lavas of the Cheviots[2] are mostly hypersthene-andesites, containing both rhombic and monoclinic pyroxenes. The freshest type shows phenocrysts of labradorite, often honeycombed with inclusions of ground-mass, crystals of hypersthene showing distinct pleochroism, and crystals and grains of pale augite, in a ground-mass of pale brown glass and felspar-microlites (fig. 61). The ground some-

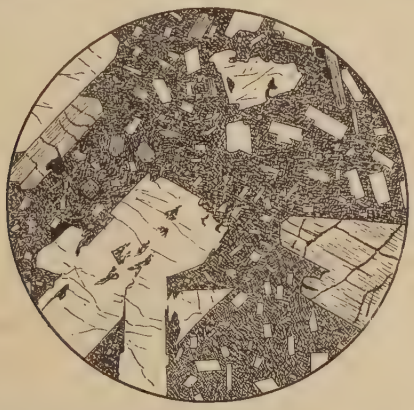

Fig. 61. Hypersthene-Andesite, Cheviot Hills, Northumberland; × 20.

Phenocrysts of labradorite and hypersthene enclosed in a fine-textured ground-mass with a large proportion of glassy base.

times has flow-structure, and shows varieties of the hyalopilitic type. The iron-ores are represented by magnetite and minute red scales of hæmatite.

Pyroxene-andesites are abundant among the Ordovician lavas of Britain. Some in the Lake District contain green pseudomorphs after a rhombic pyroxene (Falcon Crag near

[1] Kynaston, *Geology of Oban* (*Mem. Geol. Sur. Scot.* 1908) 75.

[2] Teall, *Brit. Petr.* pl. xxxvi, xxxvii, fig. 2; *G. M.* 1883, 102–106, 146–152, pl. iv, 252–254; Petersen, *G. M.* 1884, 226–234 (*Abstr.*); Watts, *Mem. Geol. Sur Eng. and Wales, Expl. of Quarter-sheet* 110 *S. W., N. S. sheet* 3 (1895) 12–13.

Keswick, *etc.*), while many others are characterized by monoclinic pyroxene only. Garnet is a frequent accessory mineral. The microstructure of the ground-mass is typically hyalopilitic. Numerous examples of these rocks have been described by Clifton Ward, Dr Bonney, Mr Hutchings[1], and Mr Walker[2]. The andesites of the Stapeley Hills (Todleth, *etc.*) in Shropshire are of the same general type as the Cheviot rocks, containing both rhombic and monoclinic pyroxenes. Pyroxene-andesites

Fig. 62. Augite-Andesite, Brunton dyke, Bingfield, Northumberland; ×20.

The only minerals seen are felspar and augite. There are, in addition, interstitial patches of brown glass, which enclose abundant crystallitic growths. The structure is typically 'intersertal.'

of Bala age are known at various localities in Ireland; *e.g.* Lambay Island[3] and Portraine[4] (Co. Dublin).

In the Tertiary volcanic series of Britain andesitic lavas play only a very subordinate part. There is, however, a group of dykes and sheets of *augite-andesite* with a wide distribution.

[1] *G. M.* 1891, 539–544.
[2] *Q. J. G. S.* (1904) lx, 70–104.
[3] Gardiner and Reynolds, *Q. J. G. S.* (1898) liv, 142–145.
[4] *Ibid.* (1897) liii, 521–527; Sollas, *Pr. Geol. Ass.* (1893) xiii, 100, with fig. 6.

Prof. Judd, who described examples from Arran[1] and Ardnamurchan[2], pointed out that they vary between holocrystalline varieties at the one extreme and rocks composed mainly of glass at the other. The most characteristic examples contain a notable amount of brown glass, often crowded with crystallites; and this tends to aggregate into patches (fig. 62), or even to collect in round vesicles[3]. Augite-andesites of this group are found in Arran, the Cumbrae Isles[4], Skye[5], Donegal[6], and Northumberland and Durham[7].

[1] *Q. J. G. S.* (1893) xlix, 541.
[2] *Ibid.* (1890) xlvi, 376–378, pl. xv.
[3] Teall, *G. M.* (1889) 481–483, pl. xiv (Tynemouth dyke).
[4] *Geol. N. Arran* (*Mem. Geol. Sur. Scot.* 1903) 119–120.
[5] *Tert. Ign. Rocks Skye* (1904) 399–401, pl. xxvi, fig. 4, and xxvii, fig. 2.
[6] Sollas, *Sci. Pr. Roy. Dubl. Soc.* (1893) viii, 91–93.
[7] Teall, *Q. J. G. S.* (1884) xl. 209–247, pl. xii, xiii; *Brit. Petr.* pl. xii, xiv.

CHAPTER XVI

BASALTS

In the *basalt* family we include all the basic lavas except those in which there is a relatively high content of alkalies, shown by the presence of minerals of the felspathoid group. The rocks range in texture from vitreous to holocrystalline. Except in a few of the latter (*dolerites*), the distinction between phenocrysts and ground-mass is commonly well marked, but the relative proportions of the two vary greatly in different types. The characteristic minerals in this family of rocks are a felspar rich in lime, augite, and olivine.

Following our principle, we shall make no distinction, as regards nomenclature and classification, between Tertiary and pre-Tertiary lavas. Foreign petrologists usually restrict the names basalt and dolerite to the newer examples, their older equivalents being denoted by such names as melaphyre augite-porphyrite, diabase, *etc.*, some of which are also applied to rocks of the hypabyssal division. It is to be observed that among these basic rocks no sharp line, definable by actual characters, can be drawn between the volcanic types and the hypabyssal.

We shall also notice in this chapter certain basic rocks, *mugearites* and *spilites*, which differ from the basalts by a very marked richness in sodic felspars.

Constituent minerals. The felspars of the basalts are of decidedly basic varieties. When distinctly porphyritic crystals occur, they seem to be usually *bytownite* or *anorthite*, while the felspars of the ground-mass are more commonly *labradorite*. The phenocrysts show albite-lamellation, often combined with pericline- and Carlsbad-twinning. Zonary structure and zonary arrangement of glass-cavities are met with. The felspars of the ground-mass have the lath-shape, and are commonly too narrow to show repeated twinning. Orthoclase is found only in certain transitional types.

The dominant pyroxenic constituent is an ordinary *augite*, and this too may occur in two generations. If so, the phenocrysts often have good crystal-forms, with octagonal cross-section: twinning is frequently seen, and sometimes zoning and hour-glass structure. The colour is usually very pale, brownish or more rarely greenish, the latter especially in the interior of a crystal. The augite of the ground-mass is either in little idiomorphic prisms or in granules, and is often very abundant. Decomposition of the augite produces chloritic substances, *etc.* A rhombic pyroxene, *hypersthene* or bronzite, occurs only in certain basalts, where it seems to some extent to take the place of olivine. It is always in idiomorphic prisms, and in the older rocks is very generally serpentinized. Some basalts, again, contain corroded crystals of *brown hornblende*, and others a little *brown mica*.

In the greater number of the basalts *olivine* is an essential constituent, and in many it is abundant, though confined, as a rule, to phenocrysts. These are sometimes well shaped crystals, sometimes more or less rounded, while in certain of the more glassy rocks hollow or skeleton crystals and crystallites occur. The mineral is colourless in thin slices. It often shows serpentine-strings following cleavage- or other cracks, and with further alteration passes into various secondary products, serpentine, carbonates, *etc.* Another common change is the production of a red or brown margin to the olivine, due to iron-oxide. Another mode of alteration sometimes met with results in the formation of brown pleochroic pseudomorphs of a mineral with a perfect cleavage and the appearance of a mica ('iddingsite').

Octahedra and grains of *magnetite* are generally abundant, and this mineral frequently recurs in a second generation in little granules. Besides this, there are frequently little opaque or deep brown scales of *ilmenite* or deep red flakes of *hæmatite*. Of other common minerals we need note only *apatite*, forming long needles, either colourless or of a faint violet or bluish tint.

Structures. The tendency to crystallization is much stronger here than in the more acid families of lavas. Again, the order of crystallization of the several constituents is less

strongly marked, the mutual relations between augite and felspar, in respect of priority, varying, while the iron-ores, though they commonly begin to crystallize at an early stage, may be in part rather late. These remarks are true of both the 'intratelluric' and the 'effusive' periods, when these are distinctly separable; but in some of the holocrystalline types the porphyritic character is not recognizable.

Very many basalts have a *holocrystalline* ground-mass. Here there are numerous varieties. Sometimes little eye-like or lenticular patches relatively rich in augite are contrasted with adjacent patches rich in felspar. When felspar-microlites make up a large part of the ground-mass, we have a structure analogous to the 'pilotaxitic' of some andesites, the flow being more or less marked. On the other hand, the ground may consist mainly of small rounded granules of augite, between which the little felspars seem to be squeezed (fig. 65, *C*). In contrast with this *granulitic* habit of the augite, an *ophitic* structure is sometimes seen in basalts rich in augite (fig. 63, *A*). Only exceptionally has the augite of the general mass an idiomorphic shape. In all these varieties the olivine usually appears in crystals of conspicuous size and partly rounded outline, while the porphyritic varieties have also idiomorphic phenocrysts of felspar and often of augite.

Again there are basalts in which the ground-mass enclosing the phenocrysts of olivine, augite, felspar, *etc.*, is *hypocrystalline*, consisting of lath-shaped felspar-microlites and granules or microlites of augite with more or less of a residual glassy base. Of this division there are various types, depending on the relative proportions of augite, felspar, and glass, and the mutual relations of the minerals. When the felspar-microlites preponderate, usually with a more or less fluxional arrangement, the ground-mass does not differ essentially from the 'hyalopilitic' type so common in the pyroxene-andesites. Vesicles are frequent in such rocks. More often, however, augite is abundantly represented in the basaltic ground-mass. Again, unindividualised glass may form the bulk of the ground. Another type of structure, already noticed in the pyroxene-andesites, is the intersertal, in which a hypocrystalline or

glassy ground-mass occurs only as angular patches in the interstices of the abundant crystals (fig. 65, *B*).

When distinct phenocrysts occur plentifully in the glassy ground-mass, we have what is sometimes called the 'vitrophyric' structure. The almost wholly vitreous type, *tachylyte*, is of very limited distribution, being found commonly as a very thin crust on some lava-flows or a narrow selvage to

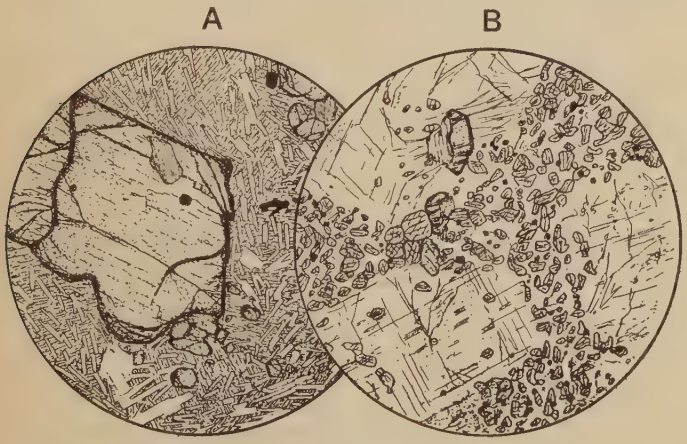

FIG. 63. OLIVINE-BASALTS, SKYE; ×20.

A. Talisker: a type rich in augite, with ophitic structure and large crystals of olivine.

B. Glen Brittle: a porphyritic type, rich in felspar, with idiomorphic augite.

basalt-dykes. It consists of a brown or yellow glass densely charged with a separation of magnetite. This is sometimes in globulites disseminated through the glass so as to render it almost opaque, or collected in cloudy patches (cumulites); at other times it forms trichites or crystallites of minute size. Perlitic structure is less common than in the obsidians. The basic glass is subject to alteration, probably involving, as a rule, hydration and other chemical changes; but the resulting

substance, known as palagonite, is still an isotropic glass, yellow, brown, or sometimes green in sections.

Radiate aggregates of felspar microlites or fibres, answering to the spherulites of acid rocks, occur in some basaltic glasses, which are known as *variolites*. These aggregates vary in size and in the regularity of their structure, which ranges from mere fan-like and sheaf-like groupings to spherules with a perfect radiate structure. They may occur isolated in a glassy matrix, or coalesce into bands, or form a densely packed mass with little or no interstitial matter. The variolites are very susceptible to alteration.

Many Tertiary and Recent basalts in Germany, Auvergne, and other regions enclose so-called '*olivine-nodules*,' which are hypidiomorphic aggregates of olivine with enstatite, diopside, and sometimes a spinellid. Similar nodules are found in some Carboniferous basalts in Derbyshire[1].

Leading types. The basic lavas of the English Lake District are wholly free from olivine. They usually carry a rhombic as well as a monoclinic pyroxene, and here, as in some other families, hypersthene may be considered as, to some extent, taking the place of the more basic silicate olivine. Such rocks may be termed *hypersthene-basalts*. The hypersthene is always converted into a light green, pleochroic, serpentinous substance comparable with bastite. The most striking variety, represented at Eycott Hill[2] and numerous other localities in the district and at Melmerby[3] near Cross Fell, has large rounded phenocrysts of labradorite (fig. 64, *A*) with Carlsbad and albite-twinning. These contain rather large opaque inclusions in the form of negative crystals and smaller enclosures with zonary disposition. In other varieties of the lavas these large crystals are not present. The ground-mass consists of slender striated prisms of plagioclase, crystals of hypersthene converted to pleochroic bastite, granules of augite, abundant magnetite, and an isotropic base.

[1] Arnold-Bemrose, *G. M.* 1910, 1–3, pl. 1.

[2] Ward, *Monthly Micro. Journ.* (1877) xvii, 240–245; Bonney, *G. M.* 1885, 76–80; Teall, *Brit. Petr.* 225–227.

[3] *Q. J. G. S.* (1891) xlvii, 517.

The Tertiary basaltic lavas of Britain, as developed in the Inner Hebrides and Antrim, are *olivine-basalts*[1]. Varieties with glassy base are not of frequent occurrence. An amygdaloidal structure is very general, and the most common contents of the amygdales are minerals of the zeolite group[2]. Embedded in these occur sometimes idiomorphic crystals of felspar, augite, and magnetite, and it appears that the infilling of the vesicles

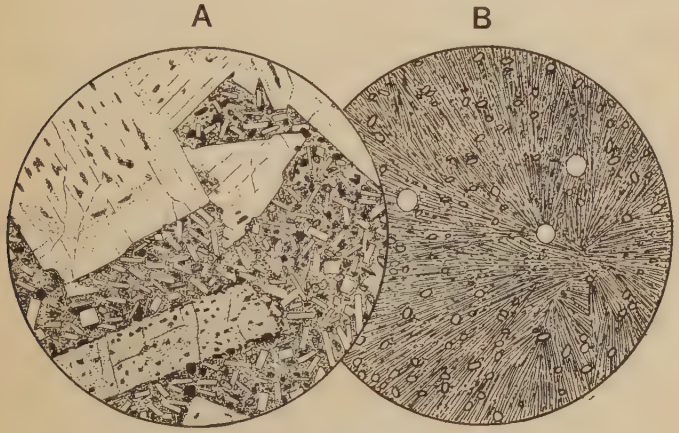

FIG. 64. BRITISH BASALTS; ×20.

A. Hypersthene-Basalt, Eycott Hill, Cumberland. In the upper part a large phenocryst of bytownite with inclusions of the ground-mass; in the lower part a pale greenish pseudomorph after hypersthene.

B. Variolitic Basalt, intrusive sheet, Point of Sleat, Skye. Shows radiating fibres of labradorite with interstitial subophitic augite and numerous little crystals of olivine. The clear round spots are vesicles.

belongs to a late stage of magmatic crystallization[3]. A few of the rocks are conspicuously porphyritic, the felspar occurring in two generations, of which the earlier is a thoroughly basic variety, sometimes near anorthite, while the latter is less basic,

[1] *Tert. Ign. Rocks Skye* (*Mem. Geol. Sur.* 1904) 32–38, pl. XVII, figs. 1–3.
[2] *Ibid.* 41–46.
[3] Strachan, *Ann. Rep. Belfast Nat. Field Club* (1908) vi, 91–98, pl. IV.

usually labradorite (fig. 63, *B*). Porphyritic augite, however, is not found, and this distinguishes the group of rocks in question from the Tertiary basalts of various European areas and also from many Carboniferous basalts of Scotland and Ireland. The augite of the ground-mass has most commonly the granulitic habit, but examples are not wanting in which the ophitic type of structure is more or less perfectly realized (fig. 63, *A*).

The Scottish Carboniferous basalts[1] include some conspicuously porphyritic rocks, which occur both as flows and as intrusive sills. In the Dunsapie type felspar, augite, and olivine are all abundant as phenocrysts; in the Craiglockhart type olivine and augite are very abundant but felspar wanting; and in the Markle type felspar is very abundant and augite wanting. There are also micro-porphyritic and non-porphyritic basalts. The commonest type has rather abundant small olivines and grains of augite in a mesh of slender felspars with microlitic augite and minute granules of magnetite (Dalmeny, Bathgate Hills, *etc.*). In another type the olivine phenocrysts are large, and the felspar-microlites are found only in small amount (lowest lavas of Bathgate Hills, Linlithgowshire).

Olivine-basalts, exhibiting some variety of microstructure (fig. 65), are extensively developed among the lavas of late geological age in America; for instance, in the Great Basin region lying between the Rocky Mts and the Sierra Nevada, in the Sierra Nevada belt, in Idaho, and elsewhere. Recent olivine-basalts occur at many localities in Colorado, New Mexico, Arizona, and about Mt Shasta and Lassen's Peak in California. Hypersthene-basalts are likewise represented among the Tertiary lavas of the western United States. Examples have been noted by Iddings[2] from the Eureka mining district in Nevada.

Of basalt-glasses or *tachylytes* examples occur at numerous

[1] Hatch, *Trans. Roy. Soc. Edin.* (1892) xxxvii, 119, pl. i, fig. 2; Falconer, *Tr. Roy. Soc. Edin.* (1906) xlv. 134–136, pl. i (Bathgate and Linlithgow Hills); Flett, *Geology of Edinburgh* (*Mem. Geol. Sur. Scot.* 1910) 316–322; Bailey, *Geology of E. Lothian* (1910) 118–121, and *Geology of Glasgow* (1911) 135–140.

[2] *Monog.* xx *U. S. Geol. Sur.* (1893) 386–394, pl. vii, fig. 2.

places in the Tertiary volcanic districts of Skye[1], Raasay, and Mull[2], and in the Co. Down (Slievenalargy)[3]; while a considerable variety of occurrences is found in the Isle of Muck[4]. These are all selvages, not of lava-flows, but of dykes and sometimes sheets. The rocks usually enclose small crystals of magnetite and sometimes of olivine, augite, and felspar. The glass is crowded with incipient growths of magnetite and

Fig. 65. American Olivine-Basalts; ×20.

A. Near Flagstaff, Arizona.

B. Rio Puerco, New Mexico: with patches of dark glassy base.

C. Near Sierra City, Sierra Nevada, California: with conspicuous crystals of felspar and augite, as well as olivine.

occasionally of other minerals. These take the form of globulites, sometimes collected into cumulites (the Beal in Skye), of margarites (Lamlash near Arran), or of numerous minute

[1] Judd and Cole, *Q. J. G. S.* (1883) xxxix, 444–462, pl. xiii, xiv; Harker, *Tertiary Igneous Rocks of Skye* (1904) 333–350, pl. xxiii and xxiv, fig. 1.

[2] Heddle, *Tr. G. S. Glasg.* (1895) x, 81–85. For localities of numerous other examples in Mull, see Kendall, *G. M.* 1888, 555–560.

[3] Rutley, *Journ. Roy. Geol. Soc. Ire.* (1877) iv, 227–232, pl. xiv.

[4] *Geol. Small Is.* (*Mem. Geol. Sur. Scot.* 1907) ch. xiii. pl. viii.

opaque rods (Sorne in Mull, *etc.*), sometimes accompanied by transparent crystallites and belonites (Gribun in Mull). Spherulites occur in some instances (Ardtun in Mull[1] and various occurrences in Skye), sometimes packed together, with polygonal boundaries, to the exclusion of any glassy matrix.

Closely allied to the spherulitic tachylytes are the rocks known as *variolite*, of which examples have been described from Tertiary dykes in the neighbourhood of Annalong, Co. Down[2], the Point of Sleat in Skye[3], and the headland of Ardmuchnish, Argyllshire[4]. The spherules show considerable variety of structure, ranging from mere fan-like groupings of felspar-microlites, or sheaf-like aggregates with a lath-shaped crystal as nucleus, to very regular, radiate, spherulitic growths. They may be closely packed to make up the entire mass of a portion of the rock, or arranged in bands, or isolated in a matrix of brown or greenish glass with cumulites, globulites, *etc.* The individual spherules are commonly from one-tenth to one-half of an inch in diameter. The best example is that from the Point of Sleat in Skye (fig. 64, *B*). Here the spherules, sometimes as much as two or three inches in diameter, are built of radiating felspar fibres with minute skeleton crystals of olivine and granules of augite, while in one variety of the rock there is a considerable amount of interstitial glassy base.

Finally we have to notice two well marked groups of basic rocks distinguished by the sodic nature of their felspathic element. The *mugearites* were first described from Tertiary sills in the Inner Hebrides[5], but are also extensively developed,

[1] Cole, *Q. J. G. S.* (1888) xliv, 300–307, pl. xi.

[2] Cole, *Sci. Pr. Roy. Dubl. Soc.* (1892) vii, 511–519, pl. xxi; (1894) viii, 220–222.

[3] Clough and Harker, *Tr. Edin. G. S.* (1899), vii, 381–389, pl. xxiii; *Tert. Ign. Rocks Skye*, 346–347, pl. xxiii, fig. 2.

[4] Bailey, *Tr. Edin. G. S.* (1905) viii, 363–371, pl. xi. For other British variolites see Miss Raisin (Lleyn), *Q. J. G. S.* (1893) xlix, 145–159, pl. i; Cole (Careg Gwladys, Anglesey), *Sci. Proc. Roy. Dubl. Soc.* (1891) vii, 112–120, pl. x; Sollas (Roundwood, Co. Wicklow), *ibid.* (1893) 99–106, figures; Lloyd Morgan and Reynolds (Bristol), *Q. J. G. S.* (1904) lx, 152, pl. xvii, fig. 3.

[5] Harker, *Tertiary Igneous Rocks of Skye* (1904) 264–266; *Geology of Small Isles* (*Mem. Geol. Sur. Scot.* 1908) 130–134.

both as lava-flows and as sills, in the Carboniferous of the Scottish Midlands[1]. A typical mugearite (fig. 66, *A*) is a non-porphyritic rock with trachytic habit. The felspar laths, which make up more than two thirds of the bulk, are of oligoclase. Augite is usually in only small amount, but there is a profusion of minute crystals of magnetite, and olivine is almost constantly

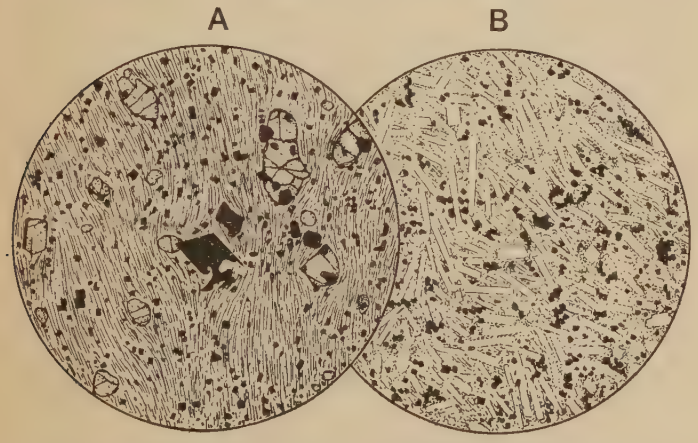

FIG. 66 BASIC ALKALINE ROCKS; ×20.

A. Mugearite, Tertiary sill, Druim na Criche, near Portree, Skye: showing densely packed slender crystals of oligoclase, with fluxional arrangement, olivine, abundant magnetite, and a little augite.

B. Spilite, Upper Devonian lava, Port Isaac, North Cornwall: composed largely of a sodic felspar with abundant little crystals of magnetite and much secondary calcite and chlorite, representing destroyed augite.

present. In the Skye rocks apatite is a rather abundant accessory constituent. Some orthoclase is present, and in the Carboniferous examples may become important, chiefly as a border to the oligoclase crystals. Some varieties carry phenocrysts of andesine.

[1] Flett, *Summary of Progress Geol. Sur.* for 1907, 119–126, with plate, and *Geol. Edinburgh* (1910) 322–323, pl. XI, fig. 5; Bailey, *Geol. E. Lothian* (1910) 123–124, pl. XII, figs. 4, 5, and *Geol. Glasgow* (1911) 140–142.

Mugearites are found also among the Ordovician lavas of Skomer Island, Pembrokeshire[1]. In the typical examples the felspar is oligoclase, while in other varieties it is either more sodic or more calcic, indicating transitions in the direction of trachyte on the one hand and basalt on the other.

In the *spilites* the sodic character of the felspathic element seems to have arisen from albitization of more calcic felspars at a late stage in the consolidation of the rocks. A change of this kind has certainly affected basaltic and doleritic rocks of various ages[2]. Spilitic lavas are well developed in the Upper Devonian of North Cornwall and South Devon[3] and in the Ordovician series of Mullion Island (Lizard)[4], Pembrokeshire, the Dolgelly district, Co Mayo[5], *etc.* The spilites are much altered amygdaloidal rocks, commonly non-porphyritic, consisting of a plexus of felspar laths with magnetite and an abundance of secondary calcite, chlorite, and quartz (fig. 66, *B*). There is no indication of olivine, and augite is seldom found fresh. The felspar is oligoclase or albite. It often has a pronounced fluxional arrangement, but this may be wanting, and the structure sometimes tends to the variolitic (Mullion Island). There are varieties carrying porphyritic crystals of felspar (Devonport).

[1] Thomas, *Q. J. G. S.* (1911) lxvii, 201–202.

[2] Bailey and Grabham, *G. M.* 1909, 250–256, pl. x, xi.

[3] Flett, *Geology of Plymouth and Liskeard* (1907) 95–97, pl. iv, fig. 1; Barrow, *Geology of Padstow* (1910) 40, pl. iv, fig. 4; Dewey and Flett, *G. M.* 1911, 202–205.

[4] Flett, *Geology of Lizard* (1912) 183–185, pl. xii, fig. 4.

[5] Gardiner and Reynolds, *Q. J. G. S.* (1912) lxviii, 95–96.

CHAPTER XVII

LEUCITE- AND NEPHELINE-BASALTS, ETC.

We shall group together for convenience various basic and ultrabasic lavas in which leucite, nepheline, and sometimes melilite are prominent constituents, with or without a lime-soda-felspar. In the phonolites and leucitophyres, described above, a potash-felspar was an essential mineral, and the rocks had other affinities with the trachytes. Although some of the rocks to be noticed resemble the phonolites and leucitophyres in certain features, they are for the most part allied rather with the basalts, being rocks of low acidity with abundant ferro-magnesian minerals.

Those types in which leucite or nepheline only partly takes the place of felspar are termed *leucite-* or *nepheline-tephrites* when free from olivine, and *leucite-* or *nepheline-basanites* when containing that mineral. For those rocks which have the felspathoid minerals to the exclusion of felspar the name *leucitite* or *nephelinite* is used when olivine is absent, and *leucite-* or *nepheline-basalt* when olivine is present. In all these divisions the leucite-bearing and the nepheline-bearing types are on the whole distinct, though the rocks characterized by either of the minerals may contain the other as an accessory.

The rocks here noticed are known chiefly from districts of Tertiary and Recent volcanic rocks. A few examples of Palæozoic age have, however, been recorded: leucite-tephrite from the Maconnais, leucitite from Siberia, *etc.*

Constituent minerals. The *leucite* of these rocks may be in two generations, differing in size. The crystals are always idiomorphic icositetrahedra, but often more or less rounded. The larger ones show feeble birefringence and the characteristic lamellar twinning. Augite microlites and granules, glass-inclusions, *etc.*, are often arranged in zones, or grouped in the centre of the crystal.

The *nepheline* in the porphyritic types is usually confined to the ground-mass. In the nephelinites and nepheline-basalts it is commonly idiomorphic, except in some of the holocrystalline rocks. In other types it often forms small allotriomorphic crystals, not easily identified, and its distribution may be local. It can sometimes be made evident by staining with fuchsine. The common alteration-products are natrolite and other soda-zeolites in radiating aggregates.

Other felspathoid minerals, *sodalite*, *haüyne*, and *nosean*, are not uncommon as phenocrysts in the rock-types richest in leucite and nepheline, but they occur only as accessories.

The yellow or colourless *melilite* is recognized by its weak double refraction, straight extinction, and peculiar microstructure. Idiomorphic crystals have a tabular habit parallel to the base, and the basal faces sometimes form concave curves. The mineral may also be quite allotriomorphic, and, when it occurs as an accessory in leucite-lavas, has sometimes the form of a framework enclosing other minerals in pœcilitic fashion (fig. 69).

This latter mode of occurrence is sometimes seen also in the *sanidine* which occurs as an accessory in some of these leucite- and nepheline-lavas, linking them with the leucitophyres and phonolites. The *plagioclase* felspars, which are found in some types of these rocks, are always of a basic variety. There may be phenocrysts with idiomorphic outline, tabular habit, albite-lamellation, zonary structure, and zones of glass-inclusions; while the felspars of the ground-mass vary from narrow laths, often only once twinned, to mere microlites. These show a tendency to spherulitic arrangement, and the phenocrysts too may form radially grouped aggregates.

The usual coloured constituent in the rocks here considered is *augite*. It often occurs in two generations, the earlier relatively large and well shaped. The colour is commonly green, but often varies in concentric zones, becoming sometimes pale violet, with distinct pleochroism, at the margin of a crystal. Again, there are sometimes two kinds of porphyritic augite, differently coloured. Some nephelinites have a purple-brown pleochroic, 'hour-glass' augite (fig. 67).

Exceptionally some of the rocks contain little yellowish green needles of *ægirine*. A brown or red-brown or red *biotite* is very common in the nepheline- and melilite-rocks, often showing resorption-phenomena. Brown *hornblende* is an occasional accessory in some rocks, and commonly shows a corrosion-border of magnetite and augite.

Olivine is an essential constituent in many of the types,

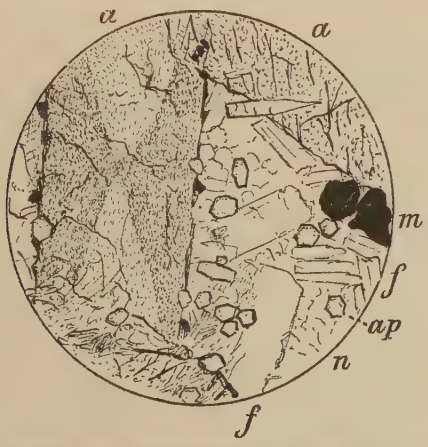

FIG. 67. NEPHELINITE (NEPHELINE-DOLERITE), LÖBAUER BERG, SAXONY; ×20.

The minerals shown are nepheline (*n*), some felspar (*f*), purplish brown augite (*a*) with hour-glass structure, magnetite (*m*), and apatite (*ap*), the rock being holocrystalline. The coming in of felspar marks a transition to the tephrite type.

and has the same general characters as in basalts. In some rocks the mineral is a hyalosiderite, and often becomes red by the separation of iron-oxide.

Iron-ores are commonly present, and in the olivine-bearing rocks often abundant. They are *magnetite* and *ilmenite*, the latter sometimes in deep brown translucent scales.

Apatite is an almost constant accessory, usually in little

prisms with the characteristic cross-jointing, though in some of the nepheline-dolerites, *etc.*, it builds larger and stouter crystals. A pale violet or blue tint, with evident dichroism, is not infrequent. Some of the leucite- and nepheline-lavas have *melanite*-garnet, brown in slices and always isotropic. A very common accessory in certain leucite- and nepheline-rocks is *perovskite*, in minute octahedra, showing in high relief in consequence of their refractive index.

Leading types. Our illustrations must be drawn mainly from extra-British sources, since few examples of any of the types here considered are known in this country. The several types to be distinguished are not always sharply marked off from one another. This is especially the case with the felspar-bearing members, the tephrites and the basanites having in great measure the same general characteristics, except for the not very considerable proportion of olivine in the latter. The differences between the leucitites and nephelinites on the one hand and the leucite- and nepheline-basalts on the other are, however, more marked, the olivine-bearing types being notably richer in the ferro-magnesian constituent (augite) and in iron-ores.

Of *leucite-tephrite* the best known examples come from the volcanic districts of Italy[1], and we may take as a type that of Tavolato near Rome. It is remarkable for an abundance of blue haüyne. There are two generations of leucite, both showing twin-lamellation. A greenish brown ægirine occurs as well as augite. Both lath-shaped plagioclase and sanidine are found, the latter sometimes occurring as an interstitial matrix to the other minerals, though in other examples there is some glassy residue. The rock also contains grains of melanite.

The lavas of Vesuvius stand between leucite-tephrite and *leucite-basanite*, olivine being, as a rule, not very abundant. The conspicuous phenocrysts are of leucite (with inclusions of brown glass and augite-microlites), plagioclase (often in radiating groups of crystals), augite, and usually olivine (fig. 68), and the same minerals, except the last, recur as constituents

[1] Washington, *Journ. Geol.* (1896) iv, 561–564 (Bolsena); *ibid.* (1897) v, 42–43 (L. Bracciano) and 246–248 (Rocca Monfina).

of the ground-mass. Magnetite and apatite are always present, and in some cases biotite is plentiful. Nepheline, sanidine, and brown hornblende are rarer, and sodalite is confined to crevices, where it seems to have been formed after the consolidation of the rock. The ground-mass is usually holocrystalline or with only a little brownish or yellowish glass, but there are vitreous and pumiceous modifications.

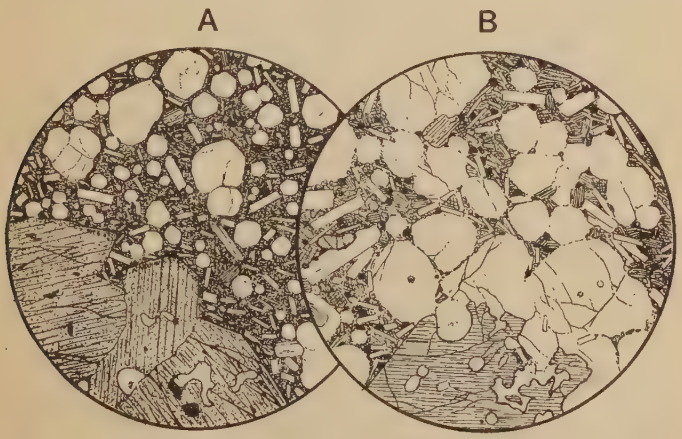

FIG. 68. LEUCITE-TEPHRITES, VESUVIUS; ×20.

A. Lava of 1813: showing clustered augite crystals, clear leucite, and labradorite in a fine-textured ground-mass with interstitial glass.

B. Atrio del Cavallo: consisting essentially of abundant leucite, augite, and labradorite.

Of *nepheline-tephrites* characteristic examples come from the Canary Islands. Augite, labradorite, and nepheline are the essential minerals, while in another type the occurrence of sanidine and haüyne marks affinities with the phonolites. Good nepheline-tephrites have been described by Zirkel[1] from the Kawsoh Mts in Nevada. These have sanidine predominating over the plagioclase: augite crystals and needles, magnetite,

[1] *Micro. Petrogr. Fortieth Parallel* (1876) 255–256.

and interstitial nepheline are the other constituents. From the Elkhead Mts and other localities in Colorado the same writer[1] notes examples of *nepheline-basanite*. One type, of coarse texture, has large crystals of olivine, idiomorphic zoned augite, plagioclase, and interstitial nepheline. Magnetite is plentiful, and biotite is often present. A nepheline-basanite has been described from North Dural in New South Wales[2], and others occur in the Dunedin district of New Zealand[3].

A fresh nepheline-basanite occurs as a dyke at Butterton in Staffordshire[4]. The only conspicuous phenocrysts are of olivine. Felspar laths (labradorite) occur in fair abundance, and little crystals of purplish augite are plentiful. The other constituents are octahedra of magnetite and abundant interstitial nepheline. In a coarse-textured variety of the rock much of the augite appears as idiomorphic phenocrysts.

Turning now to the essentially non-felspathic rocks, some of which, however, contain accessory sanidine, we find good examples of the type *leucitite* from the Alban Hills, near Rome (Capo di Bove, *etc.*). They are non-porphyritic rocks, very rich in leucite and relatively poor in augite. Other constituents are brown biotite, yellow striated melilite, and clear sanidine, all of which occur in crystal-plates enclosing the leucite and augite in pœcilitic or ophitic fashion (fig. 69). Other leucitites come from neighbouring volcanic districts.

A leucitite from the Bear-paw Mts of Montana[5] contains phenocrysts of augite and leucite in a ground-mass consisting essentially of minute skeleton leucites with very little interstitial glass. Another type very rich in leucite occurs in the Leucite Hills of Wyoming[6]. It has no phenocrysts except flakes of a yellow mica (phlogopite), and is essentially a fine-grained aggregate of little shapeless leucite crystals and microlites of

[1] *Micro. Petrogr. Fortieth Parallel* (1876) 256–258.
[2] Card, *Rec. Geol. Sur. N. S. W.* (1903) vii, 237.
[3] Marshall, *Q. J. G. S.* (1906) lxii, 409–410.
[4] Flett, *Summary of Progress Geol. Sur.* for 1909, 50–51.
[5] Weed and Pirsson, *Amer. J. Sci.* (1896) ii, 144–148, with figures.
[6] Cross, *ibid.* (1897) iv, 120–123; Kemp and Knight, *Bull. G. S. Amer.* (1903) xiv, 305–336, pl. 42.

augite. By the coming in of sanidine it graduates into the leucitophyre already mentioned (p. 170).

The *leucite-basalts* differ from the leucitites, not only in containing olivine, but also in their greater richness in the ferro-magnesian minerals in general. Numerous examples are found in the Eifel, the Saxon Erzgebirge, *etc.*

FIG. 69. LEUCITITE, CAPO DI BOVE, NEAR ROME; ×100.

Small leucites with zonally grouped inclusions are numerous, and augite and magnetite also occur. All these are enclosed by a large crystal of yellowish striated melilite. In other parts of the slide sanidine plays a similar part.

Weed and Pirsson[1] have described specimens from the Bear-paw Mts, Montana. Here the leucites, up to $\frac{1}{50}$ inch in diameter, are turbid from alteration. The other phenocrysts are olivine and pale brown zoned augite, and these minerals occur abundantly in a ground-mass of magnetite grains, augite microlites, and what appears to be a colourless glass. Others have been described from localities in New South Wales[2]. The abundant olivine has a somewhat peculiar

[1] *Amer. J. Sci.* (1896) i, 288–290.

[2] Judd, *Min. Mag.* (1887) vii, 194–195; Edgeworth David and Anderson, *Rec. Geol. Sur. N. S. W.* (1890) i, 159–162, pl. XXVIII; Curran, *Journ. Roy. Soc. N. S. W.* (1891) XXV, 210–211.

character. This, with leucite and sometimes ragged flakes of yellow mica, belongs to the earlier stage of consolidation, while the ground-mass of the rock is a finely-crystalline aggregate of leucite, yellowish green augite, and magnetite, with occasionally a little glass (fig. 70, *A*).

The *nephelinites* are rocks of only limited distribution and of very variable characters. While nepheline and augite are the essential component minerals, the coming in of sanidine,

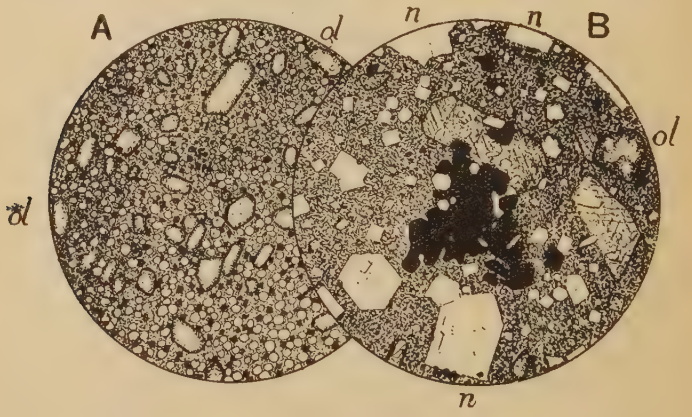

FIG. 70; ×20.

A. Leucite-Basalt, El Capitan, New South Wales: composed of olivine (*ol*), largely serpentinized, leucite, magnetite, and augite.

B. Nepheline-Basalt, Fogo, Cape Verd Isles: showing olivine, augite, nepheline, and magnetite in a fine ground-mass of smaller nepheline and augite granules.

plagioclase, nosean, melilite, olivine, *etc.*, makes transitions to various other rock-types. The texture likewise varies, and associated with true volcanic rocks there occur in some localities coarse-grained 'nepheline-dolerites,' having as their chief components nepheline and a purple pleochroic augite with hour-glass structure (fig. 67).

A typical nephelinite from Katzenbuckel, near Heidelberg, shows large idiomorphic augite phenocrysts, abundant dodeca-

hedra of nosean, and an unusual amount of apatite in large crystals, with magnetite and some brown mica. The ground-mass is of little prisms of augite, minute octahedra of magnetite, and nepheline. Locally there are patches of felspar, mostly sanidine.

The *nepheline-basalts*, much more widely distributed than nephelinites, show less variety of character. They are typically holocrystalline rocks composed of nepheline, augite, and olivine, with some magnetite and apatite. Some contain biotite in addition to augite, and haüyne may accompany the nepheline. Such rocks are known in Hesse and Thuringia, the Eifel, many parts of Saxony, Bohemia, the Canary and Cape Verd Islands (fig 70, *B*), Brazil, *etc.* The chief variation depends upon the coming in of melilite in addition to nepheline, while leucite is a less common accessory.

Nepheline-basalts are found at a few localities in Scotland, and have been described from Duncansby Head in Caithness[1] and from East Fife[2]. A specimen from Chapel Ness, near Elie, shows abundant crystals of olivine and phenocrysts of zoned augite in a ground-mass of little augite prisms, minute octahedra of magnetite, and nepheline. These rocks in Fife are intimately associated with monchiquites and limburgites. The same association is seen in the Permian lavas of Mauchline, Ayrshire, where fresh examples of nepheline-basalt are found[3]. The olivine in these rocks seems to be of a highly ferriferous variety, and gives rise to much secondary iron-oxides.

Melilite, besides occurring as an accessory constituent of some nepheline-basalts, is the distinctive mineral of the *melilite-basalts*, a comparatively rare type known chiefly from Württemberg. Phenocrysts of olivine, and often of augite and melilite, are enclosed in a fine-grained ground-mass chiefly composed of melilite and augite. Nepheline, perovskite, and picotite are among the usual accessory constituents. These rocks are not essentially different from the alnöites already described (p. 140).

[1] Flett, *Geology of Caithness* (*Mem. Geol. Sur.* 1914) 109–110.
[2] Mrs Wallace, *Tr. Edin. Geol. Soc.* (1916) x, 352.
[3] Tyrrell, *G. M.* 1912, 127.

D. SEDIMENTARY ROCKS

Under the head of sedimentary rocks we shall include the stratified deposits formed for the most part, though not exclusively, under water by the accumulation of detritus and of fragmental material of volcanic origin, by organic agency, and by chemical action or the evaporation of saline solutions. The last clause includes the secondary cementing material of many fragmental rocks, as well as the less common deposits of rock-salt, *etc.*, which do not demand special notice.

The rocks exhibit great variety of composition and characters, and in the nature of the case do not admit of any very strict petrological classification. They will be treated here under four groups: the coarser detrital deposits (*arenaceous*), the finer detrital deposits (*argillaceous*), the rocks consisting essentially of carbonate of lime (*calcareous*), and the fragmental volcanic rocks (*pyroclastic* of some authors). In all, with the exception of some of the calcareous rocks, a fragmental or '*clastic*' structure is essentially present: this, with the bedded occurrence, may be taken as characteristic of the whole.

CHAPTER XVIII

ARENACEOUS ROCKS

The arenaceous rocks are typical fragmental ('clastic') accumulations, consisting of grains of one or more minerals mechanically derived, to which may be added interstitial matter deposited in place. There is thus a distinction between original or 'allothigenous' constituents, derived from a distance, and secondary or 'authigenous' constituents, formed after the accumulation of the grains. The fragmental nature of the rocks is usually evident to the eye, and the conditions of deposition in water may be indicated by an appearance of lamination, but this is rarely so well marked as in some argillaceous rocks.

The name *sand* (Fr. sable) is reserved for incoherent deposits: when compacted by some cementing medium, they become *sandstone* or *grit*. These last two words are often used synonymously, though different writers have employed them to mark various distinctions. If a distinction be made, it is perhaps best to name the round-grained rocks sandstones, and those with angular grains grits. Such epithets as felspathic and calcareous are used to describe the nature sometimes of the grains, sometimes of the cement: they usually need no explanation. The old term *greywacke* (Ger. Grauwacke) has been revived for a complex rock with grains of quartz, felspar, and other minerals and rocks united by a cement usually siliceous. An *arkose* is a deposit derived directly from the destruction of granite or gneiss, and containing abundant felspar. A *quartzite* (of the type belonging here) is a rock consisting of grains chiefly of quartz with a quartz cement.

Derived grains. Since most sands are derived directly or indirectly (*i.e.* through the medium of earlier sedimentary deposits) from the waste of igneous or crystalline rocks, the *most usual minerals* in sand-grains are those which figure

largely in the composition of great areas of rock, such as granites, gneisses, and crystalline schists. But chemical processes tend to make a selection among these constituents; for the material is commonly affected by partial decomposition, either prior to the disintegration of the parent rock-masses, during transport, or subsequently to the accumulation of the clastic deposit. So the commonest constituents of sands are those abundant rock-forming minerals which are least prone

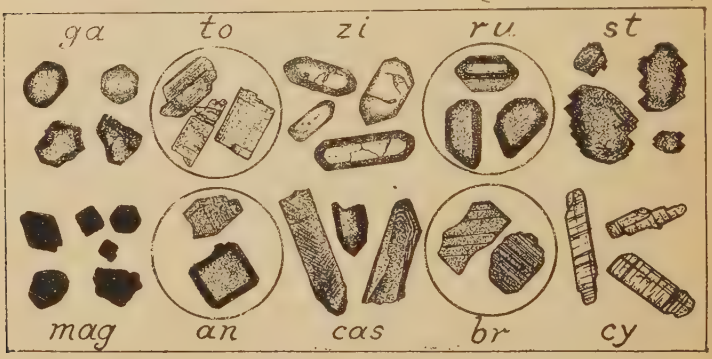

FIG. 71. ACCESSORY MINERALS OF SANDS.

The crystals within small circles are magnified 80 to 100 diameters, the others about 20. *ga*, Garnet, worn dodecahedra and fragments. *to*, Tourmaline. *zi*, Zircon. *ru*, Rutile. *st*, Staurolite, cleavage-fragments. *mag*, Magnetite, octahedra and grains. *an*, Anatase, pyramidal and tabular habits. *cas*, Cassiterite, showing zones of growth. *br*, Brookite. *cy*, Cyanite, cleavage-fragments showing the basal parting.

to chemical changes, such as quartz and white mica. Felspars, augite, hornblende, and dark micas may occur plentifully in particular deposits, but are less characteristic of sands in general, while unstable minerals like olivine rarely occur among detrital material. Certain accessories, such as zircon and rutile, are widely distributed in sands, but only in small quantity (fig. 71). Others may be abundant locally, just as the modern sands on our coasts are found in particular localities

to be rich in garnet, or flint, or tourmaline, or ilmenite (menaccanite)[1]. The admixture of few or many constituents depends on the extent and geological diversity of the drainage-area from which the material was derived. River- and lake-sands usually show less variety than those of marine origin.

Some coarse-grained deposits contain composite *rock-fragments*, *e.g.* a piece consisting of quartz and felspar with the relations characteristic of granite. Other sandstones have numerous fragments of lava. Recent deposits near the volcanic islands of the Pacific sometimes consist wholly of rolled fragments of lava, pieces of decomposing volcanic glass (palagonite), small chips of pumice, *etc.* By admixture of material of *direct* volcanic origin these volcanic sands graduate into tuffs.

The accumulations composed mainly or entirely of organic fragments (shell-sands, coral-sands, *etc.*) are more conveniently placed with the limestones.

The *form and superficial characters* of sand-grains, best studied by mounting the material dry or in water, depend upon the properties of the individual minerals and their mode of occurrence in the parent-rocks; upon the effects of attrition during transport; and sometimes upon crystalline growth subsequent to the accumulation of the deposit. Grains of felspar, hornblende, *etc.*, usually have their boundaries partly determined by the cleavages of the minerals; mica tends to form flat flakes or scales; minerals like zircon and rutile, which in the parent-rock built small well-formed individuals, often preserve their form intact. Quartz breaks into fragments of irregularly angular outline. If originally of interstitial occurrence (*e.g.* in a granite) it partly retains its highly irregular contour, and the minor irregularities produce a rather opaque appearance on the surface. Quartz-grains from a fine mica-schist, on the other hand, tend to flaky and lenticular shapes.

[1] The heavier accessories may be separated from loose sands by levigation in water, as described by Mr Dick, *A New Form of Polarising Microscope* (1890) 41–45. A useful adjunct for this purpose is the 'batêa' or Brazilian miner's pan: see Derby, *Proc. Rochester Acad. Sci.* (1891) i, 198–206. For more complete separation various solutions of high specific gravity are employed.

The degree of *rounding* produced by attrition during transport depends on the hardness of the mineral, but also on the

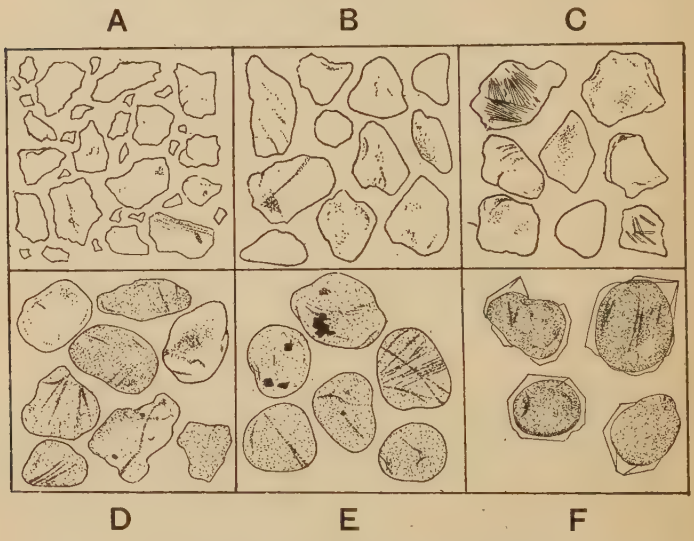

FIG. 72. QUARTZ-GRAINS FROM SANDS; ×20.

A. Glacial sand from under the Rhone Glacier: sharply angular grains, large and small commingled.

B. Beach sand, Morar, Invernessshire: grains mostly subangular.

C. Beach sand, Isle of Eigg, derived from cliffs of Jurassic sandstone: note one grain (top, left) full of sillimanite needles and another (bottom, right) enclosing needles of rutile.

D. Marine sand, Skerries Shoal, South Devon: showing an exceptional rounding, due to prolonged drifting to and fro.

E. Desert sand, Nubia: perfectly rounded.

F. Penrith Sandstone, Cumberland: a Permian desert sand with new outgrowths of quartz showing crystal-facets.

nature and duration of the mechanical agencies involved. Sands of direct glacial origin show a mixture of large and small grains, all perfectly angular (fig. 72, *A*). The grains often have

also bruised surfaces, which give a very characteristic appearance between crossed nicols. In other sands the larger grains are often more rounded than the smaller. Marine sands are in general more round-grained than those of rivers and lakes (fig. 72, *D*), while wind-borne sands, such as those of deserts, are still more rounded by friction (fig. 72, *E*). Only in these last are the smallest grains ever found to be well rounded.

The *coarseness or fineness* of sandstones may vary considerably. The sifting action of running water tends to collect in one place grains of roughly equal dimensions, but some sandstones contain grains of two very different sizes, the smaller occupying the interspaces between the larger. A very common size for the grains of quartz and felspar in many sandstones is from ·01 to ·03 inch[1].

Authigenous constituents. In addition to the clastic grains, sandstones and grits contain material deposited upon the surfaces of the grains, or filling in partially or wholly the interstices between them, and thus serving to bind them into a coherent rock. Whether formed by the recrystallization of calcareous or other matter laid down with the detritus, by the redeposition of material dissolved from the grains themselves, or by the introduction in solution of some extraneous substance, this cement must be regarded as formed in place, and its accumulation constitutes a new chapter in the history of the rock. The cementing medium itself is usually calcareous, ferruginous, siliceous, or some mixture of these.

The *calcareous cement* has probably been in most cases deposited in the form of mud, comminuted shells, *etc.*, with the original grains, but it becomes effective as a binding material only after some amount of solution and redeposition, which commonly gives it a more or less evident crystalline texture. Exceptionally a crystalline growth of calcite may enclose grains in ophitic or poecilitic fashion, as in the Fontainebleau Sandstone of the Paris Miocene, but usually the calcareous cement is strictly interstitial, and it does not always fully occupy the interspaces between the grains. In rare cases other

[1] See Bonney, *Rep. Brit. Ass.* for 1886, 601, and *Nature* (1886) xxxiv, 442.

salts, such as gypsum and barytes, may serve as a cement, and not infrequently interstitial calcite has been converted to dolomite.

Many sandstones are cemented by *ferruginous* matter or a mixture of ferruginous and calcareous. The red oxide and the brown hydrated oxide of iron occur in this way. Frequently the oxide forms a thin coating or pellicle round each grain of sand This pellicle can be removed by acid, leaving the grains colourless.

The clayey material (kaolin, very fine mica, *etc.*), which occurs interstitially in some sandstones, is probably to a great extent authigenous, representing the decomposition of felspar grains, *etc.* Similarly a chloritic mineral is not uncommon, and may be derived from the destruction in place of such minerals as hornblende and biotite.

In the tougher sandstones and grits the cementing matter is in the main *siliceous*. When the grains are angular and of various sizes, the interspaces may be very small, and the interstitial silica, concealed by the grains and perhaps by kaolin dust or iron-staining, may be difficult to observe. In more or less porous rocks, the little cementing matter required may be provided by some slight solution of the quartz-grains themselves at the points where they press on one another, as is seen in some of the sandstones of the Bristol coalfield.

When spaces have existed between the original grains, it is usually seen that the siliceous cement has been deposited in crystalline continuity with the original quartz as a *new outgrowth of the clastic grains*. The secondary enlargement of the grains is verified by the new material extinguishing simultaneously with the old between crossed nicols. Again, many sandstones which have not been compacted into hard rocks exhibit a similar new growth on the surfaces of the grains; and in this case (fig. 72, *F*) the added material often shows good crystal faces ('crystallized sand'). The enlargement is commonly clearer than the nucleus, and the division between them is marked by a line of dusty inclusions or by a thin partial coating of some deposit older than the outgrowth. Though characteristic of quartz, a similar outgrowth is occasionally

found on fragments of felspar and hornblende. In less frequent examples new-formed quartz has a radial arrangement about original grains, or is oriented independently. Again, a cement of cryptocrystalline or chalcedonic silica is known in some rocks.

When a deposit originally a quartz-sand becomes completely compacted by an interstitial cement of secondary quartz, the result is a *quartzite* of the ordinary type. Such rocks often

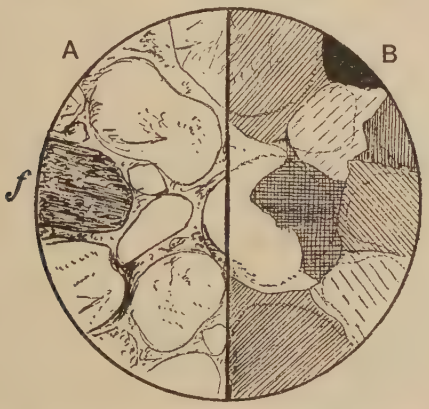

FIG. 73. QUARTZITE, STIPERSTONES, SHROPSHIRE; ×50.

A in natural light, *B* between crossed nicols. The grains are of rolled quartz with an occasional turbid felspar (*f*), and the interspaces are filled by a secondary outgrowth of quartz from the grains. The shading is diagrammatic, to indicate different interference-tints. A composite grain in the centre shows outgrowths from both portions.

consist wholly, or almost wholly, of quartz, but in a thin slice the distinction between the derived grains and the interstitial cement comes out clearly. Usually the new quartz is a crystalline outgrowth from the grains, the space between two grains being occupied by quartz, of which part is in continuity with one grain, part with the other. Between crossed nicols the slice therefore assumes the appearance of an irregular mosaic (fig. 73).

Some British examples[1]. The forms and general characters of sand-grains may be studied in modern deposits[2] and in the sands, not yet compacted into sandstone, of the later geological formations. Among the materials quartz, as a rule, largely predominates, but the sands of our modern coasts are locally rich in other minerals, such as flint, garnet, tourmaline, magnetite, ilmenite (Cornwall), silicified wood (Eigg), *etc.* Most sands contain a small proportion of certain heavy minerals, which can be separated by special methods as already remarked[3].

The form of quartz-grains depends in great measure upon their source, whether directly from crystalline rocks or from older sandstones or grits. Thus the Glacial sands of the Yorkshire coast, which must come chiefly from crystalline rocks, have sharply angular shapes, and the grains on the modern beaches of that coast, most of which are doubtless washed out of the Glacial accumulations, are scarcely more abraded. On the other hand, modern sands on the south-east coast of England, derived very largely from older arenaceous deposits, have a considerable proportion of rounded grains. On the north-west coast both Glacial and modern sands often contain extremely rounded grains, explained as being derived from the 'millet-seed' sandstones of the Trias, but these are mixed with angular quartz in various proportions. The grains of the sand-dunes on our coasts are much less rounded than those of desert sands.

The Mesozoic formations afford numerous examples of calcareous and ferruginous cements; less frequently of siliceous, although this also is sometimes found, and indeed the 'Moor Grit,' a conspicuous coarse-grained bed in the Lower Oolites

[1] Interesting information concerning British arenaceous rocks is contained in Sorby's *Presidential Address*, *Q. J. G. S.* (1880) xxxvi, and earlier papers (*Proc. Yorks. Geol. Pol. Soc.*, *etc.*). See also J. A. Phillips, *Q. J. G. S.* (1881) xxxvii, 6–27; Bonney, *Nature* (1886) xxxiv, 442–451, and *Rep. Brit. Ass.* for 1886, 601–621.

[2] For an account of the sands and other deposits now forming in the Irish Sea see Herdman, *Rep. Brit. Ass.* for 1894, 328–339, and *Pr. Liverp. G. S.* (1895) vii, 171–182; Herdman and Lomas, *ibid.* (1898) viii, 205–232.

[3] On the minerals in some Cambridgeshire sands see Rastall, *Pr. Camb. Phil. Soc.* (1913) xvii, 132–143, 161–167, and *G. M.* 1913, 252–255.

of the Yorkshire moors, is rather a quartzite than a grit[1]. In some Jurassic strata a calcareous and a siliceous cement are associated in the same rock (fig. 74, *A*). The Kellaways rock has usually a ferruginous cement. The same is true of many of the Neocomian sandstones (fig. 74, *B*), while in others the cementing medium is of granular calcite, which may be iron-

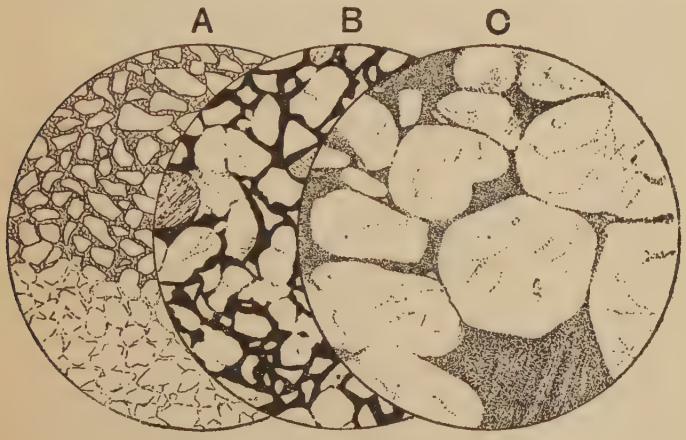

FIG. 74. BRITISH SANDSTONES; ×20.

A. Fine-grained Sandstone, Oolitic series, Isle of Eigg. The cement is calcareous in the upper part of the field and siliceous in the lower.

B. Medium-grained Sandstone, Neocomian, Shotover Hill, Oxford: with ferruginous cement.

C. Coarse Sandstone, near Llandeiniolen, Caernarvonshire. The interstitial cement is provided largely by the decomposition of grains of felspar (see lower part of field), the resulting clayey matter being squeezed between the quartz-grains and strengthened by secondary silica.

stained. Occasionally the calcite builds large plates, each enclosing many of the partly rolled quartz-grains (Spilsby in Lincolnshire, Copt Point near Folkestone). Many of these rocks have little grains of bright green glauconite with various

[1] This is often true also of the well-known 'sarsen stones' or 'greywethers,' of Wiltshire, Dorset, *etc.*; *cf.* Judd, *G. M.* 1901, 1–2.

rounded shapes, explained as casts of foraminifera. Another feature is the occurrence of little round oolitic grains of dark brown iron-ore ('carstone' of Hunstanton, and Roslyn Hill, Ely). These grains have a concentric shell structure, and, when dissolved in acid, leave a siliceous skeleton. Zircon crystals are among the denser constituents. Good examples of glauconitic sands come from the base of the Cretaceous in Antrim. The glauconite grains, unusually large and abundant, are all casts of foraminiferal chambers[1]. The glauconitic sands of the Upper Greensand in Wiltshire, Dorset, Devon, and the Isle of Wight are chiefly of coarse quartz-sand with fragments of felspar and mica, but large glauconite grains are abundant. There is often a calcareous cement[2]. Similar glauconitic sandstones of Upper Greensand age are found in the Inner Hebrides, *e.g.* at Carsaig in Mull.

The Upper Palæozoic grits and sandstones of this country often have a cement largely ferruginous or consisting of iron-oxide and quartz. Much of the Old Red Sandstone shows the investing pellicle of ferric oxide round each grain. In the Devonian of South Devon are fine-grained sandstones which, with predominant quartz, have little flakes of mica, some felspar, and small granules of tourmaline, while the interstitial matter is for the most part ferruginous.

Numerous points of interest may be studied in the New Red Sandstones. In particular, quartz-grains with a secondary outgrowth having crystal-faces are common at various horizons of the Keuper and Bunter of Shropshire, Cheshire, *etc.*, and are also exceptionally well exhibited in some coarse-grained beds of the Penrith Sandstone (Penrith Beacon, Cumberland, fig. 72, *F*). In some cases a pellicle of iron-oxide coats the new crystal-growth, and must then be long posterior to the date of the strata. Red sandstones are often of quite yielding consistency, even when the interstices are occupied by quartz. This is because of the coating of iron-oxide intervening between the interstitial quartz and the original grain. By treatment with

[1] Hume, *Q. J. G. S.* (1897) liii, 569–571.

[2] On these and other arenaceous rocks of the Upper Cretaceous see W. Hill in *Mem. Geol. Sur., Cret. Rocks Brit.*, vol. i (1900) chap. xxv.

acid the irregularly shaped patches of interstitial quartz can be isolated from the 'millet-seed' sandstones of the Trias. In these beds the perfectly rounded form of the original grains is attributed to their having been true desert-sands[1]. The Bunter Pebble-bed at Budleigh Salterton and elsewhere includes among its finer materials a considerable variety of the denser minerals[2].

Many Carboniferous grits have sharply angular grains, and were probably derived directly from crystalline rocks. The coarse-grained Millstone Grit of South Yorkshire[3] has highly irregular quartz-grains poor in fluid-cavities. There is not much fresh felspar, but argillaceous matter between the quartz-grains seems to represent it. The hard 'ganister' has angular quartz-grains which fit so closely together as to obscure the small amount of siliceous cement, and the same is true of the grits of the Bristol coalfield. In some beds in the Coal-Measures numerous flakes of muscovite lying parallel to the lamination impart a fissile character to the rocks (Bradford Flags, *etc.*). The spaces between the grains are often obscured by kaolin.

The Lower Palæozoic and older arenaceous rocks are, as a rule, thoroughly compacted, the cement being for the most part siliceous. Phillips found the quartz-cement of various Cambrian and Silurian grits (Barmouth, Harlech[4], Aberystwith, Denbighshire) permeated by a moss-like growth of a green chloritic mineral. Both coarse and fine-textured rocks are included. The quartz-grains are angular or partly rounded, and frequently contain needles of rutile and tourmaline: fluid-pores are present in some, absent in others. Some of the grits have plenty of felspars, while pyrites, garnet, and micas are occasionally noted. Specimens of the grits of Skiddaw and of the Isle of Man[5] (Santon) show fragments of slate and lava among the partly

[1] *Cf.* Mackie on the Reptiliferous Sandstone of Elgin, *Tr. Edin. G. S.* (1897) vii, 166, pl. xix, fig. 2.

[2] Thomas, *Q. J. G. S.* (1902) lvii, 620–631, pl. xxxi, xxxii.

[3] Sorby, *Pr. Yorks. Geol. Pol. Soc.* (1859) iii, 669–675. On the Millstone Grit of the Forest of Dean see Wethered, *Pr. Cottesw. F. N. Club* (1883) viii, 25–27, with plates.

[4] Greenly, *Tr. Edin. G. S.* (1897) vii, 254–258.

[5] Lamplugh, *Geol. I. Man* (*Mem. Geol. Sur.* 1902) 98–99.

rolled quartz and turbid felspars. The Ingleton rock in Yorkshire is a grit containing fragments of gneisses as well as grains and pebbles of quartz, felspars, and various lavas[1]. Volcanic grits of finer texture occur in the upper part of the Ordovician near Shap Wells, Westmorland, and these contain also calcareous matter.

The older sandstones of the Bangor and Caernarvon district and of parts of Anglesey are rather coarse-grained, consisting of well-rounded to subangular quartz with plenty of felspar. The latter mineral is often decomposed, and its clayey decomposition-products wedged in between the quartz-grains, obscuring the siliceous cement (fig. 74, *C*). Some of the rocks, however, have comparatively fresh felspar: a grit at Drys-lwyn-isaf, south of Parys Mountain, consists almost wholly of grains of oligoclase closely packed together. The prevalent type of the Torridon Sandstone is an example of a coarse sandstone rich in felspar. Besides rolled quartz-grains, often composite, it has others of microcline and fragments of quartzite and pegmatite.

The best examples of *quartzites* in England are those of Hartshill in Warwickshire and the Lickey Hills in Worcestershire, probably of pre-Cambrian age[2], and the Stiperstones in Shropshire (Ordovician). All these consist essentially of rolled quartz-grains, usually about ·02 to ·03 inch in diameter, with only very subordinate felspar, united by a clear quartz-cement, which is of the nature of a crystalline outgrowth from the grains (fig. 73). A series of quartzites forms the lower part of the Cambrian in the Assynt district, Sutherland. The uppermost bed ('Top Grit') shows large well-rolled quartz-grains, about ·05 inch in diameter, with smaller subangular grains between them. The remaining space, occupied by the siliceous cement, is obscured by opaque dust.

The orientation of the secondary quartz to conform with

[1] Tate, *Rep. Brit. Ass.* for 1890, 800; Rastall, *Pr. Yorks. Geol. Soc.* (1906) xvi, 94–98.

[2] Teall, *Brit. Petr.* pl. XLV, fig. 2, XLVI, fig. 1, and *Pr. Phil. Soc. Birm.* (1882) iii, 194–202; Watts, *Summary of Progress Geol. Sur.* for 1897, 68, and *Pr. Geol. Ass.* (1898) xv, 393, 397.

the clastic quartz-grains is not found universally. The Ightham stone, in the Lower Greensand of Kent[1], has a siliceous cement composed mainly of chalcedonic quartz set in radiate fashion about the grains. In the well-known Eocene 'puddingstone' of Hertfordshire and Kent the cement is of cryptocrystalline silica.

[1] Bonney, *G. M.* 1888, 297–300.

CHAPTER XIX

ARGILLACEOUS ROCKS

The name *clay* is used for argillaceous deposits which still retain enough moisture to be plastic. By the loss of most of their uncombined water and by other more important changes these pass into mudstones, shales, and slates. Of these terms, *mudstone* is correctly used when the rock has no marked fissile character, *shale* when it splits along the original laminæ of deposition, and *slate* when the original lamination has been superseded as a direction of weak cohesion by a new structure (slaty cleavage, Fr. schistosité, Ger. Transversalschieferung). The Continental geologists do not, as a rule, observe this distinction, but include shales and slates under the same name (Fr. schiste, Ger. Schiefer, Norw. skiffer).

Among slates it has been usual to distinguish *clay-slates* (Thonschiefer, lerskiffer), in which the material was supposed to be largely detrital matter without important new formation of minerals, from *phyllites* (Fr. phyllade), in which the rocks are largely or totally reconstituted in place (aided by dynamic agency). It is now recognized, however, that in clay-slates, and even in clays and shales, there has often been a considerable amount of mineral change in place; so that no very sharp line can be drawn between clay-slates and phyllites. The typical glossy phyllites are essentially mica-schists on a small scale, and may be described as micro-crystalline schists. We shall find it convenient to include them here, although we thereby anticipate their place under the head of dynamic metamorphism.

Constituent minerals. Owing to the extremely small dimensions of the elements, it is usually a matter of great difficulty to identify with certainty all the constituents of clays, shales, or slates. Speaking generally, these constituents include some of derived or detrital origin (allothigenous),

which were either primary minerals or decomposition-products in the parent rock-masses, and others of secondary origin, formed in place (authigenous). As regards the latter, doubt may exist in particular cases as to how far the secondary recombinations have been induced by stress (dynamic metamorphism). In many fine-grained slates no constituents are seen which can be set down with confidence as purely detrital. In all cases very thin sections and high magnifying powers must be used. Some of the denser accessory minerals may be isolated from powder by heavy solutions, or merely by washing[1].

The detrital elements may include granules of *quartz*, and less frequently of *felspars*, and scales of *mica*, with minute crystals of such accessories as *zircon*. The little flakes of biotite show more or less decomposition: Mr Hutchings finds that they give rise, not to chlorite, but to *epidote* in minute superposed tablets of light yellow colour. The iron-oxides separate out as *limonite*. *Carbonates* may occur in varying proportion. Many argillaceous rocks contain a considerable quantity of *carbonaceous matter*, finely granular and for the most part opaque: slices may be bleached by incineration on platinum foil. The *pyrites* which occurs in many slates, sometimes in relatively large crystals, is of secondary origin, and is perhaps due to the reduction of iron-compounds in the presence of organic matter. The *glauconite* found in some clays has also been formed in place[2].

The ordinary fine-grained argillaceous rocks consist in considerable part of an exceedingly fine-textured 'base' or 'paste,' very difficult to resolve, in which any truly detrital elements or their evident alteration-products are embedded. The nature of this paste has not yet been made out in any large number of cases. It was formerly regarded as consisting essentially of hydrated silicate of alumina (kaolin), *etc.* Careful studies of various clays, shales, and slates lead, however,

[1] *Cf.* Teall, *Min. Mag.* (1887) vii, 201–204. For a method of studying fine incoherent sediments see Hutchings on Sediments Dredged from the English Lakes, *G. M.* 1894, 300–303.

[2] See W. Hill on the microstructure and mineral ingredients of the Gault, *Mem. Geol. Sur., Cret. Rocks Brit.*, vol. i (1900) chap. xxiv.

to the conclusion that the material is to a great extent a very finely divided *micaceous substance* of secondary origin; and this is confirmed by chemical analyses of the rocks, which often show a considerable content of alkalies. According to Mr Hutchings[1], this main constituent of the fine-grained base is in ordinary clays and shales an impure, pale, greenish yellow mica; while in slates, where crystalline reconstruction is more advanced, it has given place to a mixture of pure muscovite and a chlorite-mineral, the two often in very intimate association. In rocks not completely regenerated there may be observed in addition much indeterminable finely granular matter, which may be conjectured to represent the finest powder of quartz, felspar, *etc.*, and perhaps *kaolin* or other products. A highly characteristic feature of the paste is the presence of an enormous number of minute needles of *rutile* ('clay-slate-needles')[2]. On account of their very small breadth and very high refractive index, the needles often appear as opaque lines, but the larger ones are transparent. The rutile is generally regarded as of secondary origin, being produced in place in association with the mica, *etc.*, the titanic acid being furnished by derived biotite. Since the changes which gave rise to these secondary products have operated in clays as well as in slates, they cannot be held to imply any advanced dynamic metamorphism, but they may still be favoured by stress.

Many slates seem to show by their chemical composition the presence of secondary free silica (in addition to any evident detrital quartz which they may contain). This is sometimes seen as a *quartz-cement*, tending to form little veins and patches; in other cases *opal* has been supposed to occur, and indeed amorphous silica may be dissolved out by caustic potash.

In some rocks, especially the Glacial tills, we must suppose that a large part of even the most impalpable material is of detrital origin. Thus in the tills of the Boston basin, Massa-

[1] *G. M.* 1896, 312–313. This author points out the advantages of cutting slices from a specimen previously ignited to redness. The resulting dehydration causes the chloritic substance to become more opaque, or assume a deeper colour, while impure mica is less affected, and the pure muscovite unchanged.

[2] *Cf.* Teall, *Min. Mag.* (1887) vii, 201–204.

chusetts, Crosby[1] found that about four-fifths of the finest grade of material was not what is commonly understood by clay, but what he terms 'rock-flour,' *i.e.* the most minute particles of pulverised quartz and other rock-forming minerals, not chemically decomposed.

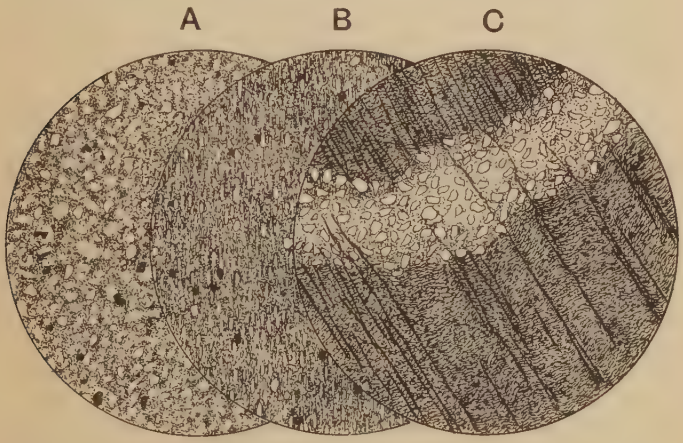

FIG. 75. SLATES; ×20.

A. Cambrian Slate, Moel Tryfaen, Caernarvonshire, cut parallel to cleavage-plane. Minute granules of quartz represent the only clastic element. The rest is mainly of muscovite and a more impure micaceous mineral, with scales of hæmatite and some calcite and quartz, all authigenous.

B. The same cut transversely to the cleavage, showing tendency to parallel arrangement of the component elements.

C. Skiddaw Slate, Bassenfell, Cumberland, with false cleavage, *viz.* close-set folds passing into faults. This structure is interrupted by a gritty seam in the slate.

Structures. Argillaceous rocks in general have a parallel arrangement of their constituent elements which is usually sufficiently marked to impart a fissile character to the mass. Slices parallel and perpendicular to the direction of fissile

[1] *Proc. Bost. Nat. Hist. Soc.* (1890) xxv, 115–172.

structure should be compared. In shales a large proportion of the minute constituent elements lie with their flat faces or long axes parallel to the layers of deposition. In true slates, *i.e.* rocks with a superinduced *cleavage-structure*, they have taken up a new direction along planes (cleavage-planes) perpendicular to the maximum compression by which the rock has been affected (fig. 75, compare *A* and *B*). The fissile structure is a consequence of the parallel arrangement of the minute elements.

The effect of the compression, accompanied by a certain partially compensating expansion along the cleavage-planes, is well seen in the deformation of concretionary spots of colour, *etc.* A spherical spot becomes distorted into an ellipsoid. A hard unyielding body, such as a crystal of pyrites or magnetite embedded in the rock, gives rise to curious phenomena. The matrix flows past the crystal, leaving a roughly eye-shaped space[1]. Such crystals have in many cases been originally coated with an envelope of chlorite, which adheres to the matrix and is torn away from the crystal. The intervening space is subsequently filled by infiltration with crystalline quartz (fig. 76, *A*).

Various structures, of frequent though local occurrence in fine-grained beds, may be styled '*false*' *and incipient cleavages*[2]. They consist sometimes in a parallel system of microscopic faults, sometimes in a regular system of minute folds. These often give a tendency to the rock to split along definite planes, *viz.* the fault-surfaces or the limbs of the folds (figs. 75, *C*, and 76, *B*). Sorby[3] has shown that such structures may be a step towards a true slaty cleavage. They may also, however, occur as later structures crossing a true cleavage (*e.g.* in various Ardennais slates and phyllites), and they are common in some fine-textured mica-schists. They are often interesting as reproducing on a minute scale the characteristic structures of mountain-ranges, such as the gradual passage of an over-fold

[1] *G. M.* 1889, 396–397.

[2] *Rep. Brit. Ass.* for 1885, 836–841. Some writers have used the terms 'close-joints cleavage' (Sorby), 'Ausweichungsclivage' (Heim), and 'strain-slip-cleavage' (Bonney) for structures of this kind.

[3] *Q. J. G. S.* (1880) xxxvi, *Proc.* 72–73.

into an overthrust fault, the relation of faults to anticlines, *etc.* A frequent result of shearing movement in finely laminated rocks is the formation of minute oblique folds inclined at about 45° to the lamination: these are pushed over until at about 30° they pass into little faults, and the faults may be further pushed over until they are lost in a general parallel-structure.

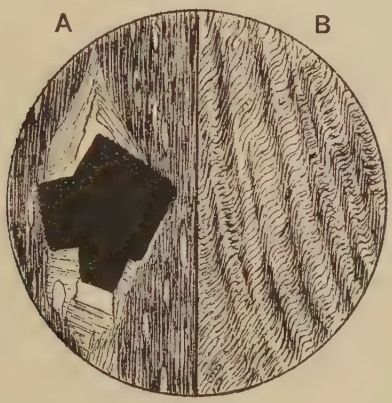

FIG. 76. SLATES.

A. Slate with crystal of pyrites, Penrhyn, near Bangor; ×5. The crystal is surrounded by an 'eye' of chlorite and quartz, as described. The mass of the slate contains little light spots, which have been deformed into an elliptic shape.

B. False cleavage in Skiddaw Slate, Brownber, near Appleby; ×20. The system of minute parallel folds causes a direction of weakness almost equivalent to cleavage.

Illustrative examples. Before describing some of the commoner types of argillaceous rocks, we may mention one of which very little is known among consolidated strata. It is represented among deposits now forming by the *abyssal red clay* which covers large areas of the ocean-floor below a depth of 2200 fathoms. This deep-sea clay is derived mainly from the destruction of volcanic products by the chemical action of sea-water. Minute fragments of volcanic rocks and minerals

are mixed with decomposition-products and with a few siliceous organisms (radiolarians, *etc.*). The brownish red colour is due to disseminated limonite. Harrison and Jukes-Browne[1] found that about two-thirds of a typical 'red clay' consists of fine argillaceous matter derived from the destruction of basic pumice or palagonite. The rest is chiefly disintegrated (but not decomposed) acid pumice; while 5 *per cent.* of the clay is matter of organic origin, principally colloid silica. The red and yellow deep-sea clays of the Tertiary in the Barbados have a very similar constitution[2]. Other rocks comparable with the abyssal red clay have been described from the Solomon Islands[3] and from Trinidad[4].

These deep-sea argillaceous deposits have characters which distinguish them from those derived from the waste of land-areas. The particles are of excessive minuteness and markedly angular in shape[5]. The minerals recognizable are those most common as constituents of volcanic rocks, such as felspar and augite, rarely quartz; while such minerals as zircon, tourmaline, *etc.*, are absent. Usually a very large proportion of the material consists of angular chips of volcanic glass and elongated fragments derived from the breaking up of pumice with capillary pores.

As another somewhat peculiar type of clay may be mentioned the *china-clay* of Cornwall, which seems to consist essentially of the mineral kaolin[6]. This, in its most recognizable form[7], builds minute colourless scales, sometimes with hexagonal outline, and of such refractive index and birefringence as closely to resemble mica. Such distinct flakes do not, however, form any large part of the finely divided material in the typical occurrences in Cornwall. Besides quartz, mica, and

[1] *Q. J. G. S.* (1895) li, 314–321.

[2] *Cf.* Miss Raisin, *Q. J. G. S.* (1892) xlviii, 180–182.

[3] Guppy, *The Solomon Is., their Geology, etc.* (1887) 81–82.

[4] Gregory, *Q. J. G. S.* (1892) xlviii, 539.

[5] Murray and Renard, 'Challenger' Report, *Deep-Sea Deposits*, pl. xxvi, xxvii, figs. 1–4; contrast with fig. 5.

[6] Some writers apply the name kaolin to the clay itself, and use 'kaolinite' for the mineral.

[7] Dick, *Min. Mag.* (1888) viii, 15–27, pl. iii. See also Howe, *Handbook to the Collection of Kaolin, Mus. Pract. Geol.* (1914) 145–158.

other impurities, tourmaline is found in some rocks composed largely of kaolin, and its production was perhaps connected with the process of 'kaolinization' of felspathic rocks[1]. In addition to the proper china-clays, formed more or less *in sitû*, there are derived clays of similar composition, such as those of Bovey Tracey.

Under certain conditions, not yet made clear, it appears that decaying igneous rocks may be deprived more or less completely of their combined silica, as well as the alkalies and dioxides, the alumina remaining in the form of hydrate, often with ferric hydrate. The *bauxite-clays* of Antrim are of this type, and probably result from the subaërial decomposition of basalt almost in place. Where quartz-bearing rocks have been subjected to this kind of change, quartz-sand remains mixed with the aluminium and iron hydrates. Much of the so-called *laterite*[2] of India and other tropical countries seems to be of this nature.

We pass on to the consideration of clays and slates of more ordinary constitution, selecting only a few examples which may be regarded as typical. A minute study of typical argillaceous rocks has been made by Mr Hutchings in the case of the *fire-clays* of the Newcastle Coal-Measures[3]. The rocks are laminated, and include coarser and finer beds. The material of true detrital origin is most abundant in the coarser beds. It seems to be derived from the destruction of granite, and consists of granules of quartz averaging ·002 to ·003 inch in diameter, granules of felspar, biotite flakes from ·01 inch downward, with the epidotic alteration, less abundant muscovite, and accessory zircon, *etc.* Besides these there is a paste, in which minute scales of secondary mica and needles of rutile are the recognizable elements.

The *shales* of the South Wales coalfield[4] were found to present similar characters, though much obscured by organic

[1] Butler, *Min. Mag.* (1887) vii, 79–80; Howe, *op. cit.* 166–189.

[2] See especially Holland, *G. M.* 1903, 59–69. On the Antrim deposits see *The Interbasaltic Rocks of N. E. Ireland* (*Mem. Geol Sur. Ire.* 1912).

[3] *G. M.* 1890, 264–273.

[4] Hutchings, *G. M.* 1896, 310.

pigment. A considerable amount of clastic muscovite, and occasionally biotite, remains with the quartz-granules, and the paste of newly-formed micaceous material has the usual rutile-needles. The Culm-measure shales of Bude in Cornwall[1] are derived from the waste of granite (in part with tourmaline) and crystalline schists. They appear to have undergone more change *in sitû* than the preceding.

The Cambrian *roofing-slates* of North Wales represent a more advanced stage of secondary change, both structural and mineralogical. They possess a strong cleavage-structure, passing indifferently through the layers of original deposition, and the more altered of them have the glossy aspect of fine-textured phyllites, in which little trace of any clastic structure survives. Detrital granules of quartz and felspar may be seen, but biotite is wanting, though little patches of epidote perhaps represent it. "The base and main constituent of all these slates is a fine-grained mica, mostly lying flat in the plane of cleavage of the rock," and rutile-needles are usually abundant. The red and purple slates contain numerous scales of red micaceous hæmatite, probably representing the limonite of less altered deposits. A number of specimens of slates, Cambrian and Ordovician, from this region have been described by Mr Hutchings[2] (fig. 75, *A*, *B*).

The Devonian slates of Cornwall (Tintagel, *etc.*) are described by the same author[3] as having suffered more alteration (ascribed to dynamic metamorphism) than the Welsh rocks. They have no clastic quartz, felspar, or biotite, and indeed some very small zircons seem to be the only derived constituents left unaltered. The main mass of the rock is of fine sericitic mica, the majority of the minute flakes being parallel to the cleavage of the rock. Minute needles of rutile are very abundant. Another very common mineral is micaceous ilmenite in flakes about ·002 inch in diameter. This is either opaque or transparent, with a deep brown colour, and sometimes encloses

[1] McMahon, *G. M.* 1890, 108–113; Hutchings, *ibid.* 188.

[2] *Pr. Liverp. G. S.* (1900) viii, 464–471, pl. I, and (1901) ix, 113–114, pl. VI, figs. E, F.

[3] *G. M.* 1889, 214–220; 1890, 317–320.

characteristic skeletons of rutile ('sagenite'). Other constituents of some of these slates are secondary quartz, calcite, chlorite, ottrelite, garnet, *etc.*

A full account, with coloured plates, has been given by Nelson Dale[1] of the phyllites of the slate-belt of New York and Vermont. These rocks consist of sericitic mica (about 40 *per cent.*), quartz, and chlorite, with carbonates, pyrites, sometimes hæmatite, zircon, and tourmaline, and in all cases minute needles of rutile. The same author[2] has recently brought together a summary account of all the more important occurrences of workable slates in the United States.

Of ordinary slaty cleavage good illustrations are afforded by the Cambrian and Ordovician in North Wales, the Devonian in Cornwall, and some other British Palæozoic rocks. Some of these (Llanberis Slates) exhibit the deformation of originally spherical spots. Various kinds of 'eyes' about enclosed pyrites crystals may be seen at Penrhyn (fig. 76, *A*), Snowdon, Blaenau Ffestiniog, Whitesand Bay, *etc.*, and in the Cowal district of Argyllshire. Special structures of the nature of *false cleavage* may be examined in the Skiddaw Slates (figs. 75, *C*, and 76, *B*) and those of Snaefell in the Isle of Man, in the debatable rocks of the Start in South Devon, and in the remarkable 'gnarled' beds of Amlwch in Anglesey and of Aberdaron, *etc.*, in the west of Caernarvonshire. These last show very beautifully all the characteristic structures of 'mountain-building' on a microscopic scale.

[1] 19*th Ann. Rep. U. S. Geol. Sur.* part III (1899) 226–269, 265, 288–290, pl. XXXV–XXXIX.

[2] *Bull.* 586 *U. S. Geol. Sur.* (1914).

CHAPTER XX

CALCAREOUS ROCKS

The different kinds of *limestones* (Fr. calcaire, Ger. Kalkstein), consisting of carbonate of lime with various impurities or foreign materials, are almost all in great measure of organic origin. The hard parts of calcareous organisms are composed of calcite or aragonite, or both, with a small quantity of phosphate, *etc.* It will be seen that aragonite is always the unstable form of carbonate of lime, and tends to be converted into the stable form, calcite. It is not always easy to distinguish the two minerals in thin slices, but Meigen's method[1] may be employed with advantage.

The impure calcareous rocks may include a considerable amount of non-calcareous material; either sand-grains (calcareous grit) or finer detritus (argillaceous limestone, marl) or volcanic *débris* (calcareous tuff).

With the limestones must be classed those rocks in which dolomite takes the place of calcite. These are called dolomite-rocks or *dolomites*, the name dolomitic limestone or magnesian limestone being more correctly applied to rocks in which both minerals are well represented. Many dolomitic rocks can be proved to have originated from ordinary limestones, the magnesia which replaced part of the lime having been derived from some external source. We shall also briefly notice certain other rocks, such as some bedded *ironstones*, which are genetically connected with the limestones, and some siliceous rocks of like origin (*cherts*).

Organic fragments. Most of the fragments of calcareous organisms that form part of rocks have something in their mineral nature, their structure, or their mode of preservation,

[1] It consists in boiling for a few minutes in a dilute solution of pure cobalt nitrate (freed from iron). Aragonite is stained lilac-red and calcite remains unaltered.

that enables us to refer them to their proper order or class, or at least sub-kingdom. Calcite structures are commonly preserved, unless dolomitization has taken place, but in the older limestones, and in many of late age, aragonite has been replaced by calcite, with obliteration of the minute structure[1].

Of the *calcareous algæ* some genera are of aragonite (Halimeda), others of calcite (Lithothamnion, *etc.*). They

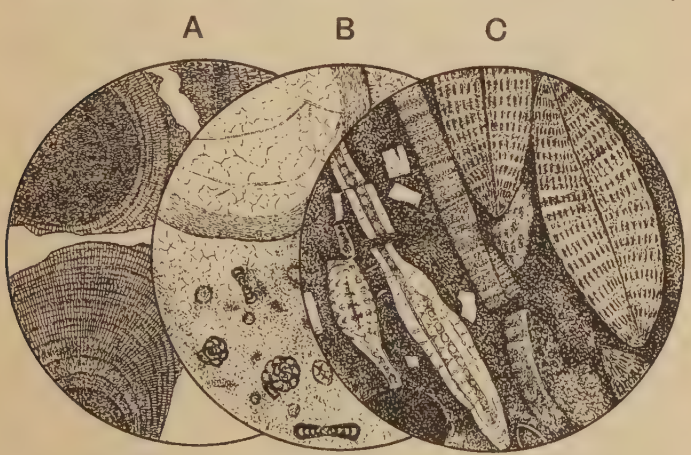

FIG. 77. CALCAREOUS ALGÆ, ETC.; ×20.

A. Recent limestone, Ascension Island; built of *Lithothamnion*.

B. Magnesian Limestone, Abergele, Denbighshire; showing polyzoans (*Fenestella*) and foraminifera.

C. Recent limestone, Tonga Islands; showing filamentous algæ (left) and foraminifera (right).

figure largely in the deposits now forming round coral-islands[2] (fig. 77, *A*, *C*), and to a less extent in some deep-sea deposits,

[1] On calcite and aragonite organisms see Sorby, *Q. J. G. S.* (1879) XXXV, *Proc.* 56–95; Cornish and Kendall, *G. M.* 1888, 66–73; Kendall, *Rep. Brit. Ass.* for 1896, 789–791; Cole and Little, *G. M.* 1911, 49–55; Horwood, *ibid.* 406–418.

[2] See Murray and Renard, '*Challenger*' *Report, Deep-Sea Deposits* (1891) pl. XIII, XIV.

while the equivalents of these rocks are recognized among the Tertiary and Recent strata in various parts of the world[1]; *e.g.* the Lithothamnion Limestone and Leitha Limestone of the Vienna basin. In some fresh-water limestones, such as those of Bembridge and of Purbeck[2], *Chara* is sometimes an important element.

The tests of calcareous *foraminifera* commonly occur entire, and are readily recognized, though in some cases the chambers become detached (Globigerina, fig. 88). The material is calcite or aragonite in different forms (answering to the division into Vitrea and Porcellanea of some authors), and probably the latter have been largely destroyed in some older limestones. Foraminifera occur in many shallow-water limestones[3], and make up a large part of the so-called coral-limestones[4], besides forming the bulk of extensive deep-sea deposits.

The interior of a foraminiferal test may be filled in by crystalline calcite, often with such a radial arrangement of fibres as to give a very perfect black cross in each chamber when examined between crossed nicols. In many modern sediments[5] formed near a continental shore-line the chambers are occupied by a deposit of green *glauconite*, which, by the removal of the calcareous test, may be left in the form of casts; and this seems to be the usual mode of origin of glauconite-sands, such as are found at various geological horizons[6].

The true *corals* consist, according to Sorby, of little fibres,

[1] Murray, *Scott. Geog. Mag.* (1890) vi, pl. I (Malta); Hill, *Q. J. G. S.* (1891) xlvii, 243–248, pl. IX (Barbados); Lister (and Murray), *ibid.* 602, 603 (Tonga Is.); Gregory, *ibid.* (1892) xlviii, 538–540 (Trinidad); Hinde, *ibid.* (1893) xlix, 230–231 (New Hebrides).

[2] Wethered, *Pr. Cottesw. F. N. Club* (1891) x, 101–102, with plate.

[3] See, *e.g.*, Guppy, *Tr. Roy. Soc. Edin.* (1885) xxxii, pl. CXLV, figs. 1, 4 (Solomon Is.); Jennings, *G. M.* 1888, pl. XIV (Orbitoidal Limestone of Borneo).

[4] See Guppy, *The Solomon Islands, Geology, etc.* (1887) 73–76, and *Tr. Roy. Soc. Edin.* (1885) xxxii, 545–581; Lister (and Murray), *Q. J. G. S.* (1891) xlvii, 602–604 (Tonga Is.).

[5] Murray and Renard, *Deep-Sea Deposits* (1891) pl. XXIV, XXV.

[6] See, *e.g.*, Murray, *Scott. Geog. Mag.* (1890) vi, 464–465, pl. II, fig. 2 (Malta); Gregory, *Q. J. G. S.* (1892) xlviii, 540 (Trinidad). *Cf.* Sollas, *ibid.* (1872) xxviii, 399 (Cambridge Greensand), and Hume, *ibid.* (1897) liii, 569–571 (U. G. S. of Woodburn, Antrim).

or in some cases granules, of aragonite; but it appears that calcite enters into the composition of some forms. Prof. Kendall states that, while almost all the reef-building forms have aragonite skeletons, all the deep-sea corals examined by him are of calcite. Of the Rugosa some consist largely of calcite fibres roughly parallel to the outlines of the several parts of the skeleton, while the mode of preservation of others seems to indicate that they were composed largely of aragonite.

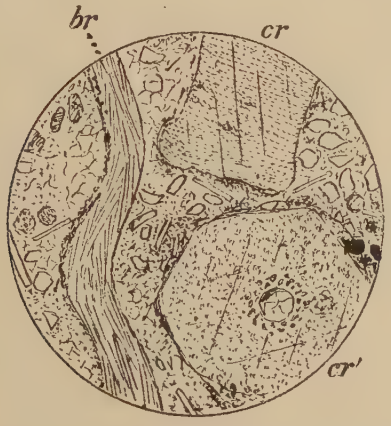

FIG. 78. LIASSIC LIMESTONE, SKYE; ×15:

showing joints of crinoid stems (*Pentacrinus*) cut longitudinally (*cr*), and transversely (*cr'*), each consisting of a single crystal of calcite; also part of a brachiopod shell (*Rhynchonella*, *br*), with its characteristic lamellar structure. The matrix is a recrystallized calcite mosaic enclosing numerous detrital grains of quartz and flakes of muscovite.

The hard parts of *echinoderms* have an unmistakable appearance. Each element (plate or joint) behaves optically as a single crystal of calcite, the larger ones showing the characteristic cleavage. The organic nature is indicated only by the external form, internal canals, *etc.* Spines of echinoids, joints of the stems of crinoids, *etc.*, may be distinguished by their size and outline (fig. 78). In the living animal the calcite

is traversed by a system of canals occupied by organic matter. In the dead skeleton these canals are apparent only when they have been filled with iron-oxide or other foreign matter: otherwise they are obliterated by a new growth of calcite in crystalline continuity with the old[1].

The structure of the hard parts of *crustacea* is also fairly constant and quite different from the preceding. The shell is built of fibres of calcite set everywhere perpendicular to the surface, the optic axis of each fibre coinciding with its length. The general outline suffices to distinguish, *e.g.* between entomostracan tests (abundant in many limestones) and fragments of trilobites.

Both calcite and aragonite enter into the composition of the *polyzoa*. The structure is characteristic, being made up of fibres set tangentially (fig. 77, *B*). Polyzoan remains are common in many deposits, such as the Carboniferous Limestone of Bristol, where they are frequently replaced by iron-oxide (fig. 79, *A*).

The shells of *brachiopods* are wholly of calcite, with a characteristic structure. It is built up by bundles of prisms, the prisms in each bundle being parallel, and showing quadrangular shapes in cross-section. These calcite prisms do not give straight extinction. The bundles are arranged obliquely to the surface of the shell, adjacent bundles abutting upon one another or partly interlocking.

Most of the *mollusca* have aragonite shells, and these, or fragments of them, are usually represented by *casts* in crystalline calcite with a purely mineral (mosaic) structure (fig. 79, *B*). To this rule there are, however, important exceptions. In some *lamellibranch* shells there is an inner layer of aragonite protected by an outer layer of calcite (Trigonia, *etc.*). In some ostreid genera (Ostrea, Pecten, Gryphæa, Inoceramus) the whole is of calcite in two distinct layers. The outer and principal layer has a prismatic structure, which differs from that of the brachiopod shells in that the little prisms are set perpendicularly

[1] On the microscopic structure of the hard parts of echinoderms, crustaceans, and mollusca see Carpenter, *Rep. Brit. Assoc.* for 1844, 1–24, pl. I–XX, and for 1847, 93–134, pl. I–XX.

to the surface, and show irregular polygonal shapes in cross-section. The prisms easily become detached and scattered through the deposit. The inner (nacreous) layer has a finely lamellar structure, sometimes with complicated interlacing.

Of the *gasteropods* again there are a few genera which have

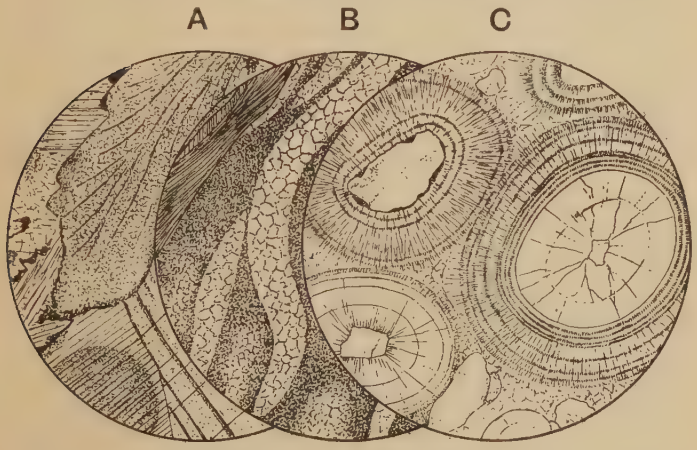

FIG. 79. LIMESTONES; ×20.

A. Carboniferous Limestone, Clifton, Bristol: showing polyzoa *etc.* in a coarsely recrystallized matrix. Part of the new calcite is grown in crystalline continuity with a crinoidal ossicle.

B. Forest Marble, Bridport; showing brachiopod fragment and chips of aragonite lamellibranch shells (replaced by new calcite).

C. Pisolite from hot springs, Vichy, Bourbonnais; with radiate structure, giving a perfect black cross between crossed nicols.

shells wholly of calcite (Scalaria) and others in which an inner layer of aragonite is covered by an outer one of calcite.

Of the *cephalopoda*, the shells of Nautilus and the ammonites were originally of aragonite, but the aptychi of the ammonites were of calcite. The belemnites had the guard of calcite, with a characteristic radial arrangement of fibres about an axis, but the phragmocone was of aragonite.

The tests of *pteropoda* consist, according to Prof. Kendall, of aragonite, and may sometimes be recognized by their form in sections. Exceptionally they form the main constituent of a limestone, and 'pteropod ooze' is one of the deep-sea deposits now forming in some parts of the ocean.

Oolitic structure. Many shallow-water limestones, of all geological ages, contain little spheroidal grains built up of successive coats of calcareous material, and these may be so numerous as to make up the chief bulk of the rock. Such rocks are called oolitic limestones, oolites, or roestone (Ger. Rogenstein). For the coarser types, in which the grains may reach the size of peas, and are often of rather irregular or flattened form, the name pisolite (Ger. Erbsenstein) is used.

In addition to the concentric-shell arrangement, there is often a more or less evident radial structure in each grain, and closer examination shows that the minute elements which build up the successive layers are set in some cases radially, in other cases parallel to the layers. As a result of either of these arrangements an oolitic grain, examined in section between crossed nicols, should give a black cross comparable with that observed in the spherulites of igneous rocks. Owing to the departure from true sphericity, the admixture of granular material not sharing the definite orientation described, and the effect of iron-staining and other secondary changes, an accurate black cross is not seen in every case.

The concentric layers have been formed upon a nucleus, which may be a chip of shell or other organic body, a quartz-granule, or merely a pellet of fine calcareous mud. Similar coatings are often to be seen upon fragments of shell, *etc.*, too large to be built up into round grains (fig. 82). Sometimes an oolitic grain has been broken and the separated fragments subsequently coated with fresh layers of calcareous deposit; or again two or three contiguous grains may be enveloped in one mantle and become a compound grain.

Oolitic grains differ as regards their material (calcite or aragonite), the orientation of their minute elements (radial or tangential), the presence or absence of finely granular calcareous matter without special orientation, or of impurities, and

in other respects. One common type, exemplified in many British limestones, has well-marked concentric shells, each of which consists largely of minute calcite prisms or fibres set radially. There may or may not be an evident radial structure in the grain as seen in a thin slice. The black cross seen in polarized light is often imperfect or vaguely defined.

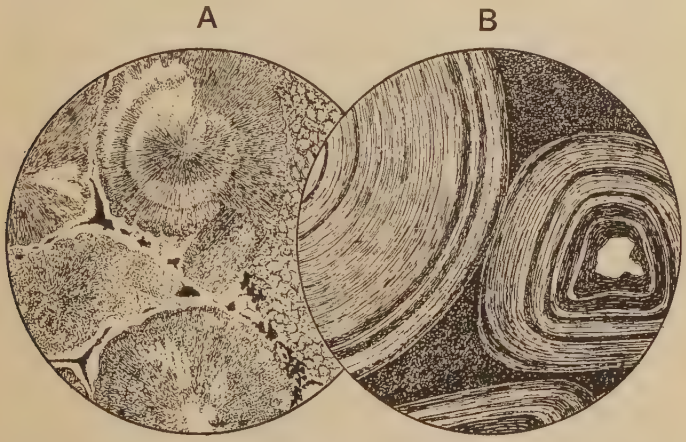

FIG. 80. OOLITIC STRUCTURES; ×20.

A. Oolitic limestone in Carboniferous, Ballagan, near Glasgow. The oolitic grains show good radiate structure, but are partly affected by recrystallization.

B. Pisolite, hot springs, Carlsbad, Bohemia. Here the minute crystals of aragonite which make up the concentric layers have a tangential arrangement. The grains give a perfect black cross between crossed nicols.

Another type is illustrated by the so-called Sprudelstein of the Carlsbad hot springs (fig. 80, *B*). Here there are well-marked concentric shells but no radial structure. The material is aragonite, and the minute elements are set mainly tangentially to the concentric layers. This gives a well-defined black cross, while the same effect is produced in the pisolite of Vichy by a regular radiate arrangement (fig. 79, *C*). It is impossible

to say with certainty to what extent aragonite oolitic grains have once been represented in our older rocks. In numerous instances the present structure of the grains shows that they have been recrystallized, but this change may probably affect calcite as well as aragonite grains. Sometimes the recrystallization can be observed in progress (fig. 80, *A*).

It is a somewhat difficult question, how far the original structure of the different types of oolitic grains is due on the one hand to mechanical aggregation or on the other to crystallization, and it further appears that organic agency may often have played an important part. In some oolitic limestones, and especially pisolites, the encrusting tubules of the calcareous alga Girvanella enter largely into the composition of the concentric layers (fig. 81), and Mr Wethered[1] assigns great importance to this and other lime-secreting organisms.

Matrix of limestones. Recognizable fragments of organisms, together with oolitic grains, if present, may make up a variable part or even the chief bulk of a limestone. The remainder, in rocks which have suffered no important secondary changes, consists of a calcareous mud in which the fragments (and oolitic grains) are embedded. This finely divided material is mostly carbonate of lime, and must be in great measure derived from the attrition and disintegration of calcareous organisms, though chemical deposition may perhaps play some part, and material may be furnished by the degradation of older limestones. Iron-compounds often occur as an impurity, producing a yellow or brown stain by oxidation. Fine sand of detrital origin is often present in shallow-water limestones, and may be abundant (calcareous grits). Similarly, an admixture of argillaceous matter gives rise to argillaceous limestones and calcareous marls, or by the presence of volcanic detritus and ashes the rock becomes a calcareous tuff.

In many limestones, and especially those belonging to the

[1] See papers cited below, but especially *Q. J. G. S.* (1895) li, 196–206, pl. VII, where the organic theory is extended to oolitic limestones in general: also *Proc. Cotteswold F. N. Club*, 1895–6. On the important part played by the calcareous algæ in the formation of rocks see Garwood, *G. M.* 1913, 440–446, 490–498, 545–553.

older formations, the original finely divided calcareous matter has been partially or wholly *recrystallized* into a granular calcite-mosaic of fine or sometimes comparatively coarse texture. Crystalline limestones or marbles are thus formed without any special conditions of the kind usually implied in the term metamorphism. The recrystallization seems to originate at certain points in the mass and spread. The process has a purifying effect, and ferruginous impurities often appear as if pushed before it to collect in particular patches. The recrystallized carbonate of lime is always calcite, aragonite being converted in the process to the stabler form. In such a crystalline matrix casts after aragonite shells may usually be recognized by a rather coarser mosaic and by a thin film of impurities marking the original outline, even when they are not coated in oolitic fashion (fig. 82). Sometimes the new-formed calcite occurs partly as a crystal-outgrowth of fragments of crinoids, *etc.*, comparable with the quartz-cement of many quartzites (fig. 79, *A*). Sometimes again the individual crystal-grains of calcite are of large size, so as to enclose numerous oolitic granules, shell-fragments, *etc.*, thus giving a structure like the ophitic and pœcilitic in some igneous rocks.

The quartz-sand, *etc.*, occurring in many limestones can be easily isolated by dissolving the rock in dilute acid, and sometimes present points of interest[1]. Minute perfect crystals of quartz may occur, sometimes evidently formed by secondary outgrowth from detrital quartz-grains (Clifton).

Some British limestones. After what has been said in the foregoing paragraphs, a few remarks on some of the more important calcareous formations of this country will be sufficient to illustrate our subject.

The Cambrian limestones of Durness, Assynt, and Skye are remarkably free from detrital impurities. They are in great part dolomitized, presenting a saccharoid texture.

The Bala Limestone of North Wales is sometimes a fine calcareous mud-stone, sometimes recrystallized. The most

[1] Wethered (Carboniferous), *Q. J. G. S.* (1888) xliv, 186–198; (Inferior Oolite), *ibid.* (1891) xlvii, 559–569.

conspicuous organic fragments are those of crinoids, which are in places very abundant, and polyzoa are also found. The Hirnant Limestone[1] has a peculiar type of oolitic structure, the grains having a chalcedonic skeleton and concentric zones rendered opaque by finely divided carbon. The Coniston Limestone of Westmorland is in its purer parts usually recrystallized throughout to a granular mass, in which the original characters are lost.

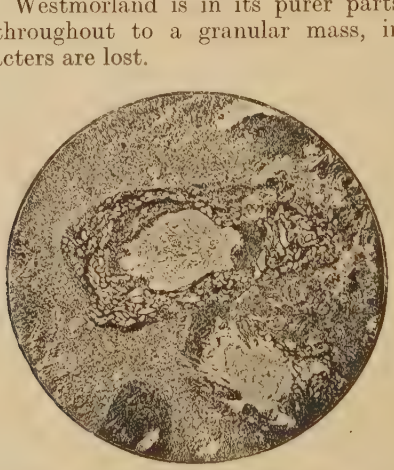

FIG. 81. OOLITIC GRAIN IN THE WENLOCK LIMESTONE, LONGHOPE; ×6.

The concentric coats are built up largely of the interlacing tubes of *Girvanella*.

The Wenlock Limestone of Dudley, with a recrystallized matrix, still preserves abundant organic fragments, especially those of crinoids, entomostracans, trilobites, corals, polyzoans, and brachiopods. It sometimes has as much as 30 *per cent.* of foreign detrital material. At Malvern the rock is largely oolitic, the grains being set in a recrystallized matrix, and sometimes themselves recrystallized (the Wych). In other places oolitic structure is largely related to an encrusting growth of Girvanella (fig. 81).

[1] Fulcher, *G. M.* 1892, 114–117, pl. IV; Harris, *Pr. Geol. Ass.* (1895) xiv, 78, pl. IV, fig. 10.

Sorby[1] has pointed out many interesting features in the Devonian limestones of Devonshire. The recognizable organic fragments are chiefly of crinoids and corals, and the finely divided calcareous matter is probably derived from the degradation of coral skeletons. This fine material has often been recrystallized in the usual fashion, the impurities being segregated into patches of finer texture. Again, rhombohedral crystals of dolomite (often ferriferous) have frequently been formed in the rocks[2], and some have become true dolomite-rocks, while a little pyrites, partly oxidized, is not uncommon. Many of the rocks show slaty cleavage in every respect similar to that noticed in argillaceous strata.

The Carboniferous limestones of Clifton, Bristol, are largely built of recognizable organic fragments. Crinoids and sometimes ostracods are especially abundant in the Lower Limestones, foraminifera and the problematical organism Calcisphera in the Middle[3]. Numerous oolitic beds occur, and in some of these Mr Wethered[4] has found the oolitic structure to be connected with the growth of Girvanella. In others the oolitic grains are in some measure replaced by iron-oxides and silica, and some of the organic fragments (especially of polyzoa) also show a ferruginous replacement. The interstitial calcareous mud is usually recrystallized as a rather coarse calcite-mosaic, and dolomitization occurs at some horizons, as is also frequently the case in the Carboniferous Limestone in other parts of Britain. In the North of England the most frequent of the recognizable organic fragments are in many cases those of crinoids, and at some horizons in Derbyshire and Yorkshire

[1] *Phil. Mag.* (1856) ser. 4, xi, 20–37. See also Wethered, *Q. J. G. S.* (1892) xlviii, 377–387, pl. ix.

[2] Wethered, *l.c.* fig. on p. 381. On the partial silicification of some beds see Chapman, *G. M.* 1893, 100–104.

[3] Wethered, *G. M.* 1899, 78–79, and *Rep. Brit. Ass.* for 1898, 862–863; see also *G. M.* 1886, 529–540, pl. xiv, xvi (Forest of Dean), and Morton's *Geol. of Liverpool* (2nd ed., 1891) 25–27 (Flintshire). The microscopic characters of some Carboniferous limestones from North Wales and from Somerset are described by Beasley, *Pr. Liverp. G. S.* (1879) iii, 359–361.

[4] *Q. J. G. S.* (1890) xlvi, 270–274, pl. xi: *cf.* Harris, *Pr. Geol. Ass.* (1895) xiv, 76–77, pl. iv, figs. 7, 8.

these constitute the main bulk of the rock, but fragments of brachiopods, corals, polyzoa, and algæ also occur, and may be abundant, while foraminifera are often very plentiful.

The Permian Magnesian Limestone is in general a true dolomite-rock, and in most cases all minute original structures have been lost in the changes which converted the rock to a granular mass of dolomite. When organic fragments are recognizable they are most frequently those of shells and polyzoa. Locally in South Yorkshire the latter bodies make up almost the whole of the rock (Brodsworth, Cadeby, *etc.*). Near Abergele in North Wales foraminifera and corals form a large part. In the Durham district occur the well-known concretions, which are essentially of calcite with radiate fibrous structure[1].

In the Lower Oolites of the Cotteswold and Bath districts[2] fragments of shells, crinoids, and polyzoa, tests of foraminifera, and other organic remains are recognized in variable proportions. Most of these limestones are oolitic, but the original structure of the oolitic grains is often destroyed by recrystallization. In the best-preserved examples Girvanella is detected at various horizons, and it is specially well exhibited in the coarse pisolite known as the 'Pea Grit[3].' The rocks yield only a little insoluble residue, consisting of detrital mineral fragments (quartz, *etc.*). The Lincolnshire Limestone and Millepore Oolite of the North of England are made up largely of oolitic grains of the ordinary type, consisting of a nucleus of a shell-fragment, a quartz-grain, or a brown pellet of mud, surrounded by numerous iron-stained coats, in which a radial structure is sometimes discernible (fig. 82). The organic fragments include chips of brachiopods and Pecten, recrystallized fragments of aragonite shells, foraminifera, valves of ostracods, pieces of echinoderms, *etc.*, in different beds: *e.g.* abundant brachiopod spines in the Rhynchonella spinosa beds. The general matrix of fine calcareous mud is almost always converted into a

[1] Garwood, *G. M.* 1891, 433–440, pl. xii.

[2] Wethered, *Q. J. G. S.* (1890) xlvi, 274–277, pl. xi; (1891) xlvii, 550–569, pl. xx; *Pr. Cottesw. F. N. Club* (1892) x, 119–120; Harris, *Pr. Geol. Ass.* (1895) xiv, 70–72, 75–76; pl. iv, figs. 1, 2, 6.

[3] Wethered, *G. M.* 1889, 197–198, pl. vi.

crystalline calcite-mosaic with localization of the ferruginous impurities, and most of the rocks contain a considerable amount of angular quartz-sand. This last feature is more prominent in the Scarborough Limestone and the Cornbrash.

The Coral Oolite of Malton is another good specimen of an oolitic limestone with recrystallized matrix. Besides foraminifera, crinoid fragments, *etc.*, it contains abundant remains of aragonite gasteropods replaced by calcite mosaic. The oolitic

Fig. 82. Oolitic Limestone, Millepore Oolite, Wharram, East Yorkshire; ×20:

showing oolitic grains (*oo*) and chips of lamellibranch shells (*s*) in a matrix which has recrystallized as a mosaic of clear calcite.

grains are sometimes large enough to be termed pisolitic, but the Girvanella noticed by Mr Wethered[1] in the Osmington pisolite, near Weymouth, is not yet recorded from Yorkshire. The last named author (*l.c.*) has described the Portland rocks[2]

[1] *G. M.* 1889, 197, pl. vi, fig. 9; *Q. J. G. S.* (1890) xlvi, 277–279, pl. xi, figs. 6–8.

[2] On the Portland Oolite see also Harris, *Pr. Geol. Ass.* (1895) xiv, 72–74, pl. iv, figs. 3, 4; Teall, *Mem. Geol. Sur.*, *Jurassic Rocks*, vol. v (1895) 186.

with their recrystallized oolitic grains. The silicification of some beds in that district will be referred to below

The microscopic characters of the English Chalk have been described fully by Hill and Jukes-Browne[1] and others. The tests of foraminifera, and especially detached chambers of Globigerina, are abundant in many examples, though they rarely form the chief constituent of the rock. They are empty in the soft chalk of the South, but filled with calcite in the hard chalk of Yorkshire. Radiolarian remains have been preserved only exceptionally[2]. Molluscan fragments, and especially the detached shell-prisms of Inoceramus, are often well represented: in the Totternhoe Stone shell-fragments form 60 to 70 *per cent.* of the rock. In most cases, however, the great bulk of the rock consists of very finely divided calcareous material, the nature of which can be studied only by rubbing the chalk with water and examining the powder. Coccoliths abound in this fine mud[3], but the minute granules are mostly such as would come from the destruction and dissolution of aragonite shells, corals, *etc.* Foreign detrital matter is rare in the Chalk, except at certain horizons, but is abundant in the Red Chalk of Hunstanton, Lincolnshire, and Yorkshire[4]. The Cambridge Greensand has rather large quartz-grains, with some mica. It also contains a considerable number of glauconite grains, usually as perfect internal casts of foraminifera[5],

[1] *Q. J. G. S.* (1886-9) xlii, 228–230 (Cambridgeshire and Hertfordshire); 242–243 (Dover); xliii, 580–585 (W. Suffolk and Norfolk); xliv, 355–357 (Lincolnshire and Yorkshire); xlv, 406–413 (Berkshire and Wiltshire); *Naturalist*, 1906, 213-214, pl. XVIII (Upp. Chalk, Lincolnshire). See also Hume, *Chem. and Micro-miner. Researches on the Up. Cret. Zones of the S. of Eng.* (1893) and on the Chalk of Antrim, *Q. J. G. S.* (1897) liii, 568–584. For a general summary of the microscopic characters of the English Chalk see Jukes-Browne, *Pr. Yorks. Geol. Pol. Soc.* (1895) xii, 385–395; and for more detailed information Hill, *Mem. Geol. Sur., Cret. Rocks*, vol. ii, chaps. XXII, XXIII, XLIII (1903) and vol. iii, chap. XXII (1904).

[2] Hill and Jukes-Browne, *Q. J. G. S.* (1895) li, 600–603 (Melbourn rock).

[3] On coccoliths in the Chalk see Sorby, *Ann. Mag. Nat. Hist.* (1861) ser. 3, viii, 193–200.

[4] On the mineral constitution of the Red Chalk and its insoluble residue see *Mem. Geol. Sur., Cret. Rocks*, vol. i (1900) 345–346.

[5] Sollas, *Q. J. G. S.* (1872) xxviii, 399.

and glauconite occurs at some higher horizons in smaller quantity. Sponge-spicules may be found in some examples. Those in the Lower Chalk of Berkshire and Wiltshire are sometimes preserved in the original colloid silica, sometimes replaced by calcite, while little globules of colloid silica (·0006 inch in diameter) occur in the rock. Glauconite grains are abundant in some parts of the 'Chalk Rock,' as well as in the Chalk Marl[1].

Deep-sea deposits. Beyond the broad belt of deposits now forming along the continental coast-lines and deriving their material from the waste of the land and from shallow-water organisms, and apart too from the special accumulations forming round coral and volcanic islands, extensive calcareous deposits are found covering large areas of the floor of the deep ocean down to about 2800 fathoms. The most widely spread of these deposits is *globigerina-ooze*, consisting largely of the tests of Globigerina and other foraminifera[2], together with a smaller proportion of other organisms, such as siliceous radiolaria, and some non-calcareous matter of volcanic origin. Associated with the foraminiferal remains are immense numbers of very minute disc-shaped bodies named *coccoliths*[3]. These calcareous discs have been detached from the surface of certain globular organisms named coccospheres, referred to the algæ. The coccoliths have a diameter of ·0002 to ·0005 inch. Associated with them are often other minute bodies in the form of slender rods with a crutch-like termination (rhabdoliths). Coccoliths and rhabdoliths are very characteristic of the deep-sea calcareous deposits, though not confined to them.

The inorganic residue of these rocks is essentially of volcanic material in a state of extremely fine division, and corresponds with the 'red clay' already noticed (p. 221).

Various foraminiferal and other limestones have been described among Tertiary and Recent strata which approximate,

[1] Hume, *l.c.* 55–56.

[2] Murray and Renard, *Deep-Sea Deposits* (1891) pl. xi, figs. 1, 5, 6; xii; xv, fig. 2.

[3] *Ibid.*, *l.c.* pl. xi, figs. 3, 4. See also Wallich, *Ann. Mag. Nat. Hist.* (1861) ser. 3, viii, 52–56.

in some cases very closely, to the essential characters of true deep-sea deposits[1].

For the sake of completeness the deep-sea deposits of siliceous composition may also be mentioned. The 'Challenger' Expedition[2] has shown that these occur over extensive tracts of the ocean-floor in its deepest portions. Characteristic types are the *diatom-ooze*, essentially an accumulation of the frustules of diatoms, and the *radiolarian ooze*, made up mainly of the tests of radiolaria. There may be some admixture of finely divided volcanic material or decomposition-products or of foraminiferal remains. The equivalents of the radiolarian ooze are found in Recent and Tertiary *radiolarian earths* such as those of Barbados[3] and Trinidad[4], and perhaps in some of the *radiolarian cherts* of the older formations. The Ordovician cherts of the south of Scotland, described by Hinde[5], show in slices a faint cloudy appearance, giving a mottled effect between crossed nicols, but are frequently veined and stained with dark brown. In the transparent parts the radiolaria show as shadowy circles defined by their interior being somewhat lighter than the surrounding matrix. In the stained parts the tests are replaced by a dark substance, and may retain much of their original structure.

Metasomatic changes in limestones. In many rocks which may be assumed to have been once ordinary limestones, the carbonate of lime has been partly, or even wholly, replaced by other substances, thus producing a change in the chemical composition of the rock (metasomatism). The most common of such changes is that in which calcite is converted into dolomite

[1] Hill, *Q. J. G. S.* (1892) xlviii, 179 (Barbados).

[2] See especially Murray and Renard, *Challenger Rep., Deep-Sea Deposits* (1891) with plates (pl. xv, *etc.*).

[3] See Jukes-Browne and Harrison, *Q. J. G. S.* (1892) xlviii, 174–175; Nicholson and Lydekker, *Palæontology*, p. 34, fig. 12.

[4] Gregory, *Q. J. G. S.* (1892) xlviii, 538–539. On a radiolarian earth from S. Australia see Hinde, *Q. J. G. S.* (1893) xlix, 221, pl. v.

[5] *Ann. Mag. Nat. Hist.* (1890) ser. 6, vi, 41–47, pl. III, IV. On a somewhat similar rock from Mullion Island, Cornwall, see Hinde, *Q. J G. S.* (1893) xlix, 215, pl. IV; on radiolarian cherts in the Culm of Devon, Cornwall, and Somerset, see Hinde and Fox, *Q. J. G. S.* (1895) li, 629–634.

by the replacement of half its lime by magnesia (*dolomitization*)[1]. The conversion may be complete, giving a true dolomite-rock, or there may remain a mixture of dolomite and calcite. In the finely granular mosaic which such rocks often present it may be difficult to distinguish the two minerals from one another without chemical tests[2]. One criterion is the much stronger tendency of dolomite to develop crystal-outlines, always those of the primitive rhombohedron (fig. 83, *A*, *C*). In coarse-grained rocks the more marked cleavage-traces of calcite and the frequency in it of lamellar twinning help to distinguish it from dolomite. Again, calcite is colourless in slices, while dolomite not infrequently shows a certain yellowish brown tint, due to some isomorphous mixture of the lime-iron-carbonate ankerite.

In many cases the rocks give evidence of shrinkage during the process of dolomitization. There are often crevices and cavities, which, however, may be filled subsequently by an infiltration of calcite. Some dolomitized oolitic limestones show a little cavity in the centre of each oolitic grain (Magnesian Limestone near Hartlepool).

Good examples of more or less perfectly dolomitized rocks occur in the Durness Limestone of Sutherland (fig. 83, *B*), the Bala and Coniston Limestones, the Devonian of Devonshire (fig. 83, *A*), the Carboniferous Limestone of many parts of England and Ireland, and the Permian Magnesian Limestone. The dolomitized Carboniferous Limestones of Derbyshire[3], the Isle of Man (fig. 83, *C*), South Wales[4], and Ireland[5] are in general highly crystalline, and all trace of organic structures is obliterated. A common type seems to be that in which the predominant dolomite, in more or less imperfect crystals, is cemented by calcite.

[1] See Dixon, *Geology of Swansea* (*Mem. Geol. Surv.* 1907) 13–20, pl. I, II, and Parsons, *G. M.* 1918, 246–258, pl. XI.

[2] Lemberg has given a microchemical test applicable to rock-slices. With a solution of aluminium chloride and logwood calcite becomes stained in five or ten minutes to a violet colour, while dolomite is unaffected.

[3] Rutley, *Q. J. G. S.* (1894) I, 381–382, pl. XIX, figs. 5, 6.

[4] Watts, *Mem. Geol. Surv., S. Wales Coalfield*, part II (1900) 34–36, pl. I.

[5] Hardman, *Pr. Roy. Ir. Acad.* (1876) ser. 2, ii, 723–726.

Sorby described the Magnesian Limestone north of Nottingham as comparatively coarse-textured, with evident rhombohedral crystals. The usual type in Durham is often fine-grained, the elements being of irregular form. Sometimes an interlocking arrangement of the granules, aided by the presence of little vacant spaces, gives a certain flexibility to the rock[1]

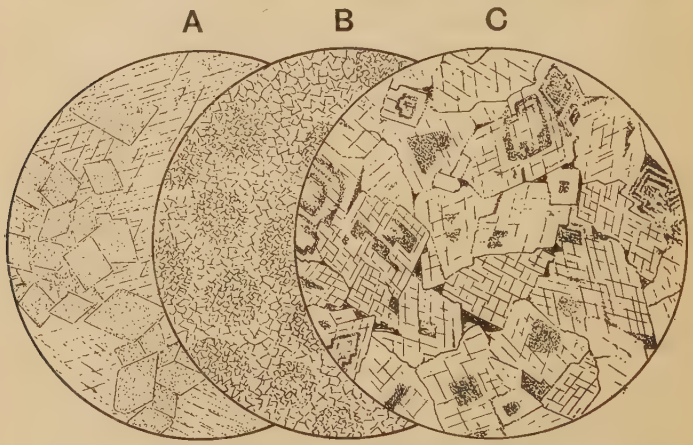

Fig. 83. Dolomite-rocks; ×20.

A. Devonian Limestone, Torquay; showing an early stage of dolomitization: rhombs of dolomite in a matrix of calcite.

B. Dolomitized Durness Limestone, near Loch Assynt, Sutherland. The original oolitic structure is still discernible by the finer texture in small round spots.

C. Dolomitized Carboniferous Limestone, Castletown, Isle of Man; with ferruginous material, partly marking zones of growth in the dolomite crystals.

(Marsden). The little cavities or pores are, however, as in other dolomitic rocks, often occupied by crystalline calcite.

Again, certain *ironstones* have evidently been formed[2] by

[1] Card, *G. M.* 1892, 117–124.

[2] See Sorby, *l.c.* pp. 54–55; Judd, *Geol. of Rutland*, 117–138; Hudleston, *Pr. Geol. Ass.* (1889) xi, 117–127; Cole and Jennings,

metasomatic changes from limestones. The process consists first in the replacement of calcite by ferrous carbonate (chalybite), and further, in many cases, in an oxidation of the latter, giving rise to magnetite, hæmatite, or limonite. The oolitic limestones seem to be specially liable to this kind of alteration, and the oolitic grains themselves show the most advanced stage, the outer part of each grain being converted into magnetite or limonite, while the matrix of the rock remains as chalybite or in part calcite (fig. 84, *A* and *B*, illustrating successive stages). The chalybite matrix is fine-textured, and the mineral often shows imperfect crystal-form, each crystal sometimes enclosing a nucleus of decomposing pyrites (fig. 84, *D*). In a more advanced stage of change patches of limonite replace the chalybite of the matrix, and even calcite shells of Pecten, *etc.*, are converted into hæmatite or limonite (*e.g.* the Dogger of the Peak in Yorkshire)[1]. Valuable oolitic ironstones are worked in this country. That of Rosedale (Dogger) is magnetite; the Cleveland Main Seam[2] (Middle Lias) shows various stages of transformation and various admixtures of earthy matter; the Jurassic ores of Northampton and Rutland have specially the limonite type of alteration; and the Neocomian ores of Tealby and Claxby in Lincolnshire are similar. Liassic ironstones are worked also at Frodingham in Lincolnshire (fig. 84, *A*) and on the Isle of Raasay[3]. An oolitic ironstone with more gritty impurities occurs at Abbotsbury and Westbury in the Corallian group of the Isle of Purbeck[4].

If the grains of an oolitic iron-ore be dissolved in acid, each leaves a shell or skeleton of silica, soluble in caustic potash. This silica must have been introduced at some stage of the alteration of the original limestone. A similar siliceous skeleton is sometimes found in the grains of oolitic limestones where no

Q. J. G. S. (1889) xlv, 426–427; Teall in *Mem. Geol. Sur., Jurassic Rocks of Britain,* vol. iii, p. 302; vol. iv, pl. II, *etc.*

[1] Sorby, *Naturalist,* 1906, 354, 357.

[2] For figures of this and other oolitic ironstones see *Mem. Geol. Sur., Jurassic Rocks,* vol. iv, pl. II.

[3] Thorneycroft, *Tr. Edin. Geol. Soc.* (1914) x, 200, pl. XXII.

[4] Strahan, *Mem. Geol. Sur., Geol. I. Purb.* (1898) 39; Teall in *Mem. Geol. Sur., Jurassic Rocks,* vol. v (1895) 324; see also vol. iv, pl. II, fig. 12.

ferruginous replacement has taken place, or, again, silica may more or less replace the calcareous matter between the grains[1]. Although *silicification* is perhaps less common than some of the other metasomatic changes noticed above, it is found in

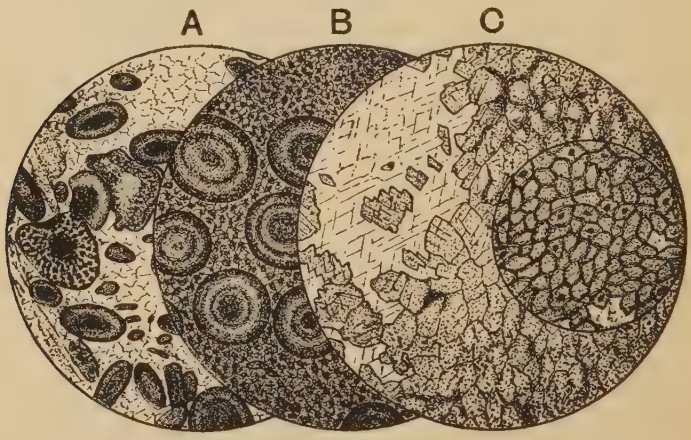

FIG. 84. IRONSTONES; ×20.

A. Oolitic Limestone in an early stage of conversion, Lias, Frodingham, Lincolnshire. The oolitic grains and certain classes of organic fragments are replaced by iron-oxide, the matrix being still a mosaic of calcite.

B. Oolitic Ironstone, Neocomian, Claxby, Lincolnshire. Here the matrix has been replaced by chalybite, and this oxidized in spots.

C. Ironstone, Dogger, Blea Wyke, Yorkshire: showing an aggregate of crystalline chalybite, with some residual clear calcite.

D. (Small inset circle, × 100.) Ironstone in Lower Oolites, Scarborough. A fine-grained aggregate of chalybite, with only incipient oxidation; some grains containing a nucleus of pyrites.

numerous limestones of various ages. Sometimes the replacement of carbonate of lime by silica is confined to the organic remains, but in other cases it affects the whole body of the rock (*e.g.* some cherts). Parts of the Carboniferous limestones

[1] Chapman, *G. M.* 1893, 100–104 (Devonian, Ilfracombe).

of Clifton show examples of oolitic grains and organic fragments replaced by a mixture of limonite and silica. Good examples of cherts formed by the silicification of limestone (matrix and fossils alike) are found in the Portland Beds of the South of England[1]. In some chert-bands in the Durness Limestone of Sutherland the oolitic structure is still discernible (Stronchrubie near Ichnadamph). Similar oolitic cherts occur in the Corallian of Yorkshire, in the Portlandian of St Alban's Head[2], and in the Carboniferous of South Wales[3].

Still another metasomatic change met with in some calcareous rocks is *phosphatization*. This usually affects some or all of the organic remains, or phosphatic nodules are formed having fossils of various kinds as nuclei. The phosphate of lime is presumably itself derived from organic bodies, but it is not clear to what extent it has been supplied contemporaneously with the deposit which contains the nodules. Deposits rich in phosphate occur at various horizons in the formations of this country: the Cambridge Greensand may be taken as an example, where the fossils are largely phosphatized, and also serve to some extent as the nuclei of nodules. In other instances phosphate of lime occurs as casts of foraminifera[4] or as grains more or less definitely replacing those bodies[5].

[1] Miss Raisin. *Pr. Geol. Ass.* (1903) xviii, 76–80, pl. xiv, xv.

[2] Teall, *Mem. Geol. Sur., Geol. I. Purbeck* (1898) 63, and *Jurassic Rocks*, vol. v (1895), 186.

[3] Watts, *Mem. Geol. Sur., S. Wales Coalfield*, part ii (1900) 36.

[4] Chapman, *Q. J. G. S.* (1892) xlviii, 514–518, pl. xv.

[5] Strahan, *Q. J. G. S.* (1891) xlvii, 357–362 (Chalk, Taplow); (1896) lii, 465 (Lewes).

CHAPTER XXI

PYROCLASTIC ROCKS

The fragmental volcanic rocks are in general the products of explosive action. The ejected material varies from the finest dust to pieces several inches, or even feet, in diameter, but the coarsest types do not require special notice here.

What is known as *volcanic dust* or fine ash is no doubt partly due to the comminution of rocks and crystals by friction during the explosion, but a great part of it must represent lava blown out from the vent in liquid form and solidified almost instantaneously in the air. It doubtless solidifies as glass, but may, of course, be subsequently devitrified. The bodies known as volcanic *bombs* and *lapilli* are of very various sizes. They may have spheroidal or more peculiar forms; or again they may be irregularly shaped or fitted together. Some kind of concentric structure, with a nucleus and an outer crust, is often seen, or the exterior may be scoriaceous. In many volcanic accumulations *crystals* play an important part. They are commonly idiomorphic, though frequently broken, and belong to the minerals common in lavas. They may sometimes be torn from solid rocks, but more generally they must have been contained in a fluid matrix before the eruption. We also find *rock-fragments*, either angular or, in submarine deposits, partly rolled and worn. They are commonly of lava for the most part, shattered and blown out by the explosion; but we also find pieces of igneous rocks which must have come from greater depths, or fragments of slate, grit, limestone, *etc.*, representing strata broken through, and often showing evident metamorphism. The larger 'ejected blocks' are frequently of these foreign and non-volcanic rocks.

The rocks formed by the accumulation of these various materials have received many names. The term *ash*, applied to the finer incoherent products of modern volcanoes, is sometimes used in a more extended sense; but the older, more or

less compacted, deposits of ash-material are usually called *tuffs*. A large proportion of them were evidently laid down under water: subaërial accumulations have less frequently been preserved from destruction. Rosenbusch, in describing the ancient acid tuffs, divides them into compact tuffs, crystal-tuffs, and agglomeratic tuffs, and the division may be applied

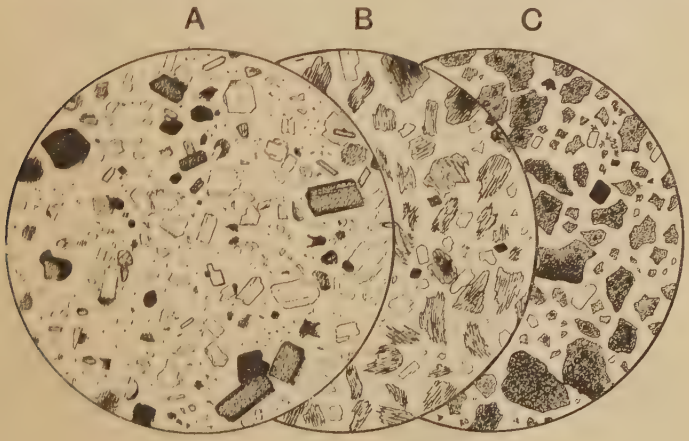

FIG. 85. VOLCANIC ASHES; ×20.

A. Mt. Pelée, Martinique, eruption of 1902: mainly composed of crystals of plagioclase, magnetite, hypersthene (dark), and augite (paler), with a small amount of glassy matter.

B. Near Cotopaxi, Ecuador: composed mainly of shreds of andesitic pumice, but with crystals of felspar and magnetite.

C. Falcon Island, Tonga group: chiefly little fragments of light brown glass with small steam-pores.

to rocks of other composition; but, since the relative proportions of dust, crystals, and lapilli, *etc.*, may vary to any extent, no precise divisional lines can be drawn. If angular rock-fragments be largely represented, the deposit is termed a *volcanic breccia*, or if the fragments be rounded, a *volcanic conglomerate*.

According to the nature of the material, the rocks may often be spoken of as 'rhyolite-tuff,' 'trachyte-tuff,' *etc.*, or, again, 'andesite-breccia,' 'trachyte-conglomerate,' and so forth; but, owing to the admixture of various materials, the rocks do not always correspond exactly even with contemporaneous lavas directly associated with them.

Further, when deposited under water, the volcanic material may become mixed with ordinary detritus or with calcareous matter, and so we have earthy tuffs, calcareous tuffs, *etc.*, some of which are fossiliferous.

General characters. Excepting crystal-fragments and material derived from the pulverization of pre-existing solid rocks, the fragmental products of volcanic eruptions are ejected in the liquid state, and solidify very rapidly in the air. The liquid is not merely shot out like a projectile urged by a force from behind. The force comes from the sudden expansion of steam and other gases dissolved in the lava itself and released everywhere throughout the liquid mass when relief of pressure causes these volatile constituents to flash suddenly into the gaseous state. It follows that any coherent masses (bombs, *etc.*) which are thrown out are, as a rule, highly vesicular or scoriaceous, and are readily shattered into smaller fragments. But it also follows, if the gases released are very abundant, that the liquid lava itself is shattered from within and scattered into drops, or even into the most minute particles. The content of gases at high pressure, which determines the grade of comminution of the material ejected, defines also the degree of violence of the eruption, and between these two things there is therefore a natural correlation. The products of the most violent (Krakatoan) explosions are of the nature of impalpable dust. The ash from a more ordinary (Vulcanian) type of outbreak has not this excessively fine texture, and a Strombolian eruption gives rise especially to fine lapilli or consolidated drops. Crystals and crystal-fragments make only a minor part of these accumulations; but, if crystallization is already well advanced in the viscous liquid at the time of the outburst, the crystal element may preponderate (Peléan type, fig. 85, *A*). The products of the least violent (Hawaiian) eruptions are (in

addition to lava-flows) chiefly scoriæ and bombs, the latter being consolidated giant drops of lava.

In a thin slice true lapilli can often be recognized by a rounded outline, or a vesicular structure, or an opacity due to finely divided magnetite, and some concentric arrangement is always apparent. The name 'lapilli' is sometimes incorrectly applied to fragments of comminuted glassy lava: these have a characteristic outline with indentations made by broken vesicles. They are often the chief constituent of the tuffs of basalts and augite-andesites, and are very generally converted into the transparent brown or yellow, or more rarely green, substance known as palagonite (p. 186). The tuffs of rhyolites and dacites, again, are often composed largely of shreds of colourless glass, or devitrified glass, with concave outlines, resulting from the breaking up of pumiceous or highly vesicular glassy lava (fig. 86). This appearance is highly characteristic, and is sometimes termed 'ash-structure' (Ger. Bogenstructur).

In the finest volcanic ashes the glass-fragments have a peculiar structure and a characteristic form. This is due to the immense number of contained steam-bubbles, which were drawn out into minute tubes, causing the glass to break into linear shapes with a longitudinal striation. The glass is distinguished from comminuted felspar by the absence of true rectilineal boundaries and the isotropic character. The minute fragments are colourless, except in the case of basic glasses, which may be of a brown tint. According to Murray and Renard[1], the characteristic appearance of these glass-fragments may be recognized even in excessively small particles (less than ·0002 inch), while the distinctive properties of most minerals cannot be detected in fragments of smaller dimensions than ·002 inch. The minerals commonly present are the familiar constituents of volcanic rocks—especially plagioclase, pyroxenes, and magnetite, for many of these very fine volcanic dusts are of the nature of pyroxene-andesite. The crystals are often coated with glass or have glass adherent. The authors named find precisely similar material to be widely distributed in modern deep-sea deposits, where it accumulates from the

[1] See especially *Nature* (1884) xxix, 585–589.

fall of wind-borne dust and the disintegration of floating pumice.

In tuffs formed not far from a volcanic centre, crystals of recognizable size, perfect or broken, are often embedded in a fine-textured matrix. These frequently show a characteristic arrangement, standing with their long axes vertical or roughly perpendicular to the lamination of the matrix, as if dropped into their place from above (fig. 87).

In any except comparatively young tuffs the original character of the finely divided material is often obscured by secondary changes, the loose texture of the deposits rendering them peculiarly liable to alteration. According to the nature of the rock, such minerals as quartz, sericitic mica, chlorite, calcite, *etc.*, are developed at the expense of the original dust. Silicification is very common in the acid tuffs. Again, it will easily be understood that fine-textured tuffs may exhibit precisely the same phenomena of slaty cleavage as those seen in argillaceous sediments.

Illustrative examples. The Palæozoic and earlier volcanic series in Wales and England afford many examples of *rhyolite-tuffs*. Those of Llyn Padarn, Llanberis[1], are often agglomeratic, and contain lapilli. They have acquired a schistose character from crushing.

Some of the fine-textured rocks which have been styled 'porcellanite' and 'hälleflinta' are acid tuffs compacted by secondary silica and other substances. Examples occur in the St David's district (Clegyr Bridge, *etc.*) and in Charnwood Forest (Nanpanton). Rocks of the same general aspect in the Lake District (Bow Fell, *etc.*) are fine tuffs of intermediate composition.

Ordovician rhyolite-tuffs, some with the characteristic microstructure of broken pumice (fig. 86, *A*) are found on Aran Mowddwy[2] and among the 'Upper Ashes' of the Arenig

[1] Bonney, *Q. J. G. S.* (1879) xxxv, 312; Green, *ibid.* (1885) xli, 77; Teall, *Brit. Petr.* pl. xlv, fig. 1.

[2] Cope, *Pr. Liverp. G. S.* (1897) viii, pl. iv, v.

district[1], near Builth[2], at various places in Pembrokeshire (St David's[3], Fishguard[4], Llanrian), at Pontesford Hill in Shropshire[5], and near Malvern (Knighton).

Rhyolitic tuffs are found abundantly in the Snowdon district. Embedded crystals usually occur (Glyder Fawr, *etc.*), but do not make up any large part of the mass. There are,

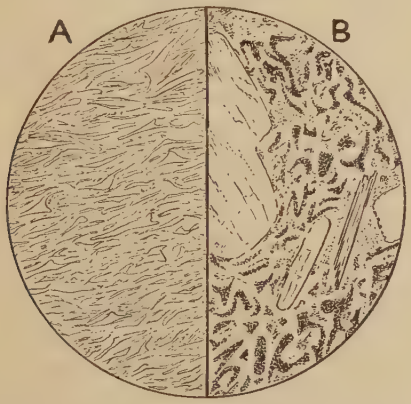

FIG. 86. ANCIENT PUMICEOUS TUFFS; ×20.

A. Rhyolitic Tuff (Ordovician), Llanrian, Pembrokeshire. Originally composed wholly of glass-fragments, the outlines of which are still partly discernible, despite their alteration; typical 'ash-structure.'

B. Andesitic Tuff (Old Red Sandstone), Inverinan, Argyllshire. The outlines of many of the fragments are indicated, owing to their being charged with magnetite-dust. There are also partly rounded crystals of plagioclase and an occasional flake of biotite.

however, beds made up very largely of small rock-fragments and broken crystals, lying in a fine-textured matrix or united by a brown ferruginous paste. The rock-fragments are of

[1] Fearnsides, *Q. J. G. S.* (1905) lxi, 626.
[2] Rutley, *ibid.* (1902) lviii, p. 30, with figure, and pl. II.
[3] Geikie, *ibid.* (1883) xxxix, 297–301.
[4] Reed, *ibid.* (1895) li, 175.
[5] Boulton, *ibid.* (1904) lx, 474–475, pl. XLIII, fig. 4.

various quartz-porphyries and granophyres, and sometimes detached spherulites; the crystals are of acid felspar and decomposed augite (near Llanbedrog, *etc.*)[1].

Of *andesite-tuffs* some with the general composition of hornblende- and especially of mica-andesites, enclosing broken crystals and lapilli, occur in the Old Red Sandstone of the Oban district[2] (fig. 86, *B*). Tuffs of Ordovician age at Bail Hill, near Sanquhar in Ayrshire[3], contain abundant well-shaped crystals of hornblende and augite, up to $\frac{1}{4}$ inch in length, with some of felspar, and may be regarded as crystal-tuffs of the hornblende-andesite type. A rock with similar crystals occurs at Rhobell Fawr in Merioneth[4].

The pyroxene-andesites are much more widely represented in fragmental accumulations of various ages. To this type belong the ejectamenta of many of the most violent outbursts of modern volcanoes. The volcanic dust thrown out from Krakatau in the great eruption of 1883 has been described by several writers[5]. About nine-tenths of the material consists of glass fragments with the characteristic features noticed above. The remainder is of comminuted crystals of plagioclase, magnetite, enstatite, and augite, the whole having the composition of an acid pyroxene-andesite. So likewise had the volcanic dust from Mt Pelée and from the Soufrière in St Vincent[6] (1902–3), but in this the crystal element preponderated greatly over the glass (fig. 85, *A*).

The cleaved tuffs of Cader Idris[7] in Merioneth contain plenty of slate-fragments with felspar-crystals and particles of scoriaceous andesite-glass converted into green palagonite, all set in a fine ashy matrix. Fragments of shale occur also at

[1] Harker, *Bala Volc. Ser. Caern.* 27.

[2] Kynaston, *Tr. Edin. G. S.* (1901) viii, 87–90, pl. III.

[3] Teall, *Ann. Rep. Geol. Sur.* for 1896, 39.

[4] Cole, *G. M.* 1893, 343.

[5] Murray and Renard, *Nature* (1884) xxix, 585–589; Cole, *Proc. Geol. Ass.* (1884) viii, 332–335; Joly, *Proc. Roy. Dubl. Soc.* (1884) N. S. iv, 291–299, pl. XII, XIII; Judd, *Rep. Krak. Comm. Roy. Soc.* (1888) 38–41, pl. IV.

[6] Flett, *Q. J. G. S.* (1902) lviii, 368–369.

[7] Cole and Jennings, *ibid.* (1889) xlv, 423–431.

some horizons in the important series of pyroclastic rocks in the Arenig district, which are for the most part of the nature of hypersthene-andesites[1]. Some other ancient tuffs consist largely of little fragments of formerly glassy and sometimes pumiceous andesite, now converted into a palagonite-like material of yellow or brown colour, as at Snead[2] and Pontesford Hill[3] in Shropshire. Pyroxene-andesite-tuffs of Silurian age are found in the Mendips[4]. They are largely crystal-tuffs, and pass into ashy conglomerates.

FIG. 87. BASIC TUFF, ORDOVICIAN, WET SLEDDALE NEAR SHAP; ×20.

The bulk of the rock is of very fine particles, but encloses some rock-fragments and numerous crystals of felspar, which tend to stand perpendicularly to the lamination of the matrix.

The majority of the Ordovician tuffs in the Lake District correspond in general composition with andesites and with basic andesites or basalts, but many of them have in addition angular fragments of rhyolite[5]. Crystals of felspar are often

[1] Fearnsides, *Q. J. G. S.* (1905), lxi, 623–626.
[2] Cole, *ibid.* (1888) xliv, pl. XI, fig. 5.
[3] Boulton, *ibid.* (1904) lx, 463–469, pl. XLII and XLIII, figs. 1, 2.
[4] Reynolds, *ibid.* (1907) lxiii, 233, pl. XVIII.
[5] Walker, *ibid.* (1904) lx, 95–98, pl. XIV, figs. 1, 2.

seen, but do not make up a large part of the rocks, which are essentially of the compact type in most cases (fig. 87). Rolled pieces of lava of small dimensions may occur. In some localities the rocks consist mainly of a mixture of small lapilli with fragments of slate, grit, *etc.*, often metamorphosed. Mr Hutchings has described an example from Falcon Crag near Keswick[1].

Some interesting fragmental rocks of *basaltic* composition occur in the old volcanic series of St David's, of early Cambrian or pre-Cambrian age[2]. They are agglomeratic tuffs, consisting chiefly of little fragments of basic lava, sometimes rounded but usually angular or subangular. In some there is very little matrix: it consists of fine *débris* of the same material as the larger fragments.

Among the basaltic rocks crystal-tuffs seem to be almost unrepresented. A common type consists of lapilli of basalt (glassy or altered) cemented by calcite, aragonite, limonite, *etc.* Widely distributed is the *palagonite* type of Waltershausen, described from Sicily, Iceland, the islands of the Pacific, *etc.* This consists chiefly of little fragments of altered glassy basalt, usually of brown colour, often vesicular, and sometimes enclosing a few crystals of augite, olivine, or basic plagioclase; while the cementing material is obtained from the decomposition of the fragments, or may include calcite derived from calcareous matter contemporaneously deposited or by infiltration from without (fig. 88).

Submarine tuffs of basic composition occur abundantly in the Carboniferous in the basin of the Firth of Forth. Most of them contain some admixture of detrital or calcareous matter, but characteristic examples of tuffs, and in particular of palagonite-tuffs, are found[3]. The common type is crowded with fragments of vesicular lava, mostly glassy and in the state of palagonite. The vesicles are occupied by chlorite and calcite. The matrix of these rocks has probably consisted of finely divided material of the same general nature as the larger

[1] *G. M.* 1891, 462.
[2] Geikie, *Q. J. G. S.* (1883) xxxix, 295–300, pl. IX, figs. 1, 2.
[3] Geikie, *Trans. Roy. Soc. Edin.* (1879) xxix, 513–516, pl. XII, fig. 10.

fragments, but its structure is completely obscured by secondary changes, and the mass is stained green or brown. Tuffs of essentially similar characters are found in the Carboniferous of the Bristol neighbourhood[1], the Isle of Man[2], and the Limerick district. Those in Derbyshire[3] are in great part composed of true lapilli, often bordered, and having numerous vesicles not broken by the outline of the lapillus. The material

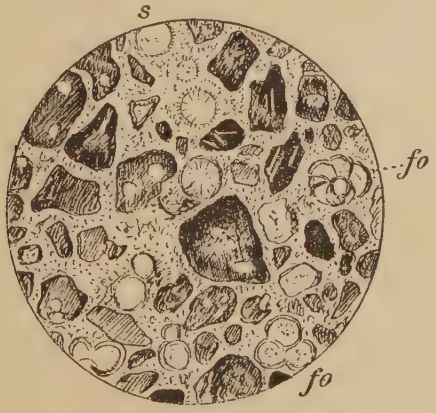

Fig. 88. Calcareous Tuff, Eua, Tonga Islands; ×20.

The fragments are mainly of brown-stained andesitic and basic lava, more or less glassy and altered to palagonite. These, with tests of foraminifera (*fo*), are enclosed in a calcareous matrix. Each foraminiferal chamber is occupied by calcite with radial fibrous structure, giving a perfect black cross between crossed nicols, and the same is seen in the little spherical bodies (*s*), which are doubtless detached chambers of *Globigerina*.

is a brown glass with globulites and crystallites, and encloses crystals of olivine or plagioclase. These minerals are often replaced by calcite, and the same substance fills the vesicles and forms the cement of the rock.

[1] Lloyd-Morgan and Reynolds, *Q. J. G. S.* (1904) lx, 154–155.
[2] Hobson, *ibid.* (1891) xlvii, 442–443.
[3] Arnold-Bemrose, *ibid.* (1894) l, 625–642; pl. xxiv, figs. 4, 5.

Fine-grained tuffs, and in a less degree agglomerates, may receive, as already mentioned, a secondary *cleavage-structure* precisely similar to that observed in argillaceous rocks; and the cleavage is often accompanied by mineralogical changes. The cleaved tuffs or ash-slates of the Lake District[1] are of intermediate, and sometimes perhaps basic, composition, and the finely divided matrix has undergone great secondary changes. Chlorite and dust or granules of calcite are often conspicuous, and when these have been removed by acid from the powdered rock, or from very thin slices, other minerals may be detected, especially minute sericitic mica, which gives bright polarization-tints. The needles of rutile, so characteristic of clay-slates, are not found, but there are sometimes granules of sphene (*e.g.* Kentmere). In some of these slates minute garnets play an important part (*e.g.* Mosedale, near Shap). In general there has been an abundant separation of silica, partly as quartz, partly perhaps as chalcedony.

[1] Hutchings, *G. M.* 1892, 154–161, 218–228; *Pr. Liverp. G. S.* (1901) ix, 106–112, pl. vi, vii.

E. METAMORPHISM

Using the term 'metamorphism' in a broad sense, we understand by it the production of new minerals, or new structures, or both, in pre-existing rock-masses. We must limit such a conception by supposing on the one hand that the changes produced are sufficient to give a distinctive new character to the rock as a whole, and on the other hand that they do not involve the loss of individuality of a rock-mass (*e.g.* bodily fusion must be excluded). We shall moreover exclude the various chemical and mineralogical changes produced in rocks by reaction with the atmosphere and atmospheric waters under superficial conditions. These are in general metasomatic as well as metamorphic changes. Some of the more important, such as serpentinization and dolomitization, have already been noticed.

The transformations now to be considered under the head of metamorphism are those which are brought about in solid rock-masses under the influence of high temperature and powerful stress. We may accordingly distinguish *thermal* metamorphism, due to heat, and *dynamic* metamorphism, due to stress. These can to some extent be considered separately, and we shall examine some of their results in the following pages. But it is important to realize that this does not represent a comprehensive view of the subject. The great group of rocks known as the *crystalline-schists* have, for the most part, been recrystallized under the joint influence of high temperature and powerful shearing stress, and the physical conditions thus implied cannot be conceived merely as a superposition of thermal upon dynamic metamorphism. Metamorphism of this most general type is too complex a subject to be included in an elementary treatment, and our survey must therefore remain in this respect incomplete.

Metamorphic changes are in part *mineralogical* (in most cases without any very important metasomatism), in part *structural*. These two lines of change are so connected that they cannot be considered separately: roughly we may say that mineralogical modifications are the more prominent in thermal metamorphism, and structural rearrangements in dynamic metamorphism.

CHAPTER XXII

THERMAL METAMORPHISM

Under this head we include all changes produced in solid rock-masses by the influence of high temperature. In the simplest case this is brought about by the intrusion of an igneous magma in the neighbourhood ('contact' or 'local' metamorphism of many authors); but we must also recognize the effects of heat mechanically generated (thermal being then associated with dynamic phenomena), and those due to the internal heat of the Earth in a rise of the isogeotherms. These latter especially may affect rock-masses on a regional scale, and inevitably involve the dynamic element. We shall avoid complication by drawing our examples, so far as is possible, from cases of thermal metamorphism produced by igneous intrusions.

Characteristic minerals. It will be convenient to refer briefly to the commoner minerals formed in thermal metamorphism, some of them being unknown or rare in igneous rocks. *Quartz* and felspars are widely distributed in metamorphic rocks of various kinds. The felspars include *orthoclase*, *albite*, *anorthite*, and various intermediate members of the plagioclase series. They are often perfectly clear, and when they occur as minute shapeless granules in a mosaic they may easily be mistaken for quartz without special optical tests[1]. The larger grains show cleavage and sometimes characteristic twinning or some approach to crystal outline.

Both *muscovite* and *biotite* are found in metamorphosed rocks, the latter being very widely distributed. It is apparently a haughtonite and always strongly pleochroic, with a deep reddish brown colour or, for vibrations parallel to the cleavage-traces, a very deep brown with a noticeable greenish

[1] Becke has given a staining method, using aniline blue after etching with hydrofluoric acid. Plagioclase is deeply coloured, orthoclase only slightly affected, and quartz unchanged.

tone. Intensely pleochroic haloes surround certain inclusions. Less usual than brown mica as a conspicuous mineral is a green *ripidolite* or a yellowish or greenish *chlorite*, which belong to a lower grade of temperature. Less frequently occurs *chloritoid* or its variety ottrelite, often showing a repeated lamellar twinning parallel to the base and a modification of hour-glass structure (fig. 91, *A*). This seems, however, to be one of those minerals which are produced only when shearing stress has co-operated with a more or less elevated temperature. We will distinguish them for convenience as 'stress-minerals.'

Highly characteristic of the metamorphism of argillaceous rocks are silicates rich in alumina. *Andalusite* forms often well-shaped crystals with the prism-form and usually some traces of the prismatic cleavage. It is recognized by its moderately high refractive index with low double refraction (about the same as in labradorite) and straight extinction. When it shows any colour, it is pleochroic, giving a rose tint for longitudinal and a very faint green for transverse vibrations. It may be quite clear, or may contain numerous inclusions, certain enclosed minerals being surrounded by a pleochroic halo (bright yellow to colourless). In *chiastolite* the elongated crystals contain a large amount of foreign matter, apparently carbonaceous, arranged in the fashion peculiar to the mineral (fig. 90, *A*). *Sillimanite* (*fibrolite*) builds elongated prisms or needles with high refractive index, straight extinction, and a birefringence equal to that of augite (fig. 89, *A*). The needles are often crowded in matted aggregates embedded in quartz ('Faserkiesel' or 'quartz sillimanitisé'). *Cyanite* or disthene is found less commonly, building more or less rounded crystals or grains, with pinacoidal cleavage and a cross-fracture corresponding with a gliding-plane (fig. 92, *B*). In thin sections it is colourless or pale blue, with pleochroism, and, owing to its high refractive index, shows a strong relief. Longitudinal sections give extinction-angles up to 31°. *Staurolite* forms good crystals, the larger ones always crowded with various inclusions (fig. 92, *A*). When fresh, it is yellowish or reddish brown with distinct pleochroism, and strong refringence and birefringence. This mineral, however, and in varying degree all the aluminous silicates, are very liable to decomposition, the characteristic

product being white mica in minute scales (the 'shimmer-aggregate' of Barrow). Cyanite is distinctively a stress-mineral, characteristic of crystalline schists, and this seems to be true also of staurolite. *Cordierite* is sometimes less easily recognized. It is commonly in shapeless grains crowded with inclusions, but sometimes builds pseudo-hexagonal prisms, basal sections of which occasionally show the curious triple twinning. The mineral rarely shows its colour and pleochroism in thin slices, but is sometimes stained of a yellow tint. The refractive index and double refraction are low.

The metamorphism of calcareous rocks gives rise to numerous silicates rich in lime, or in lime and magnesia. The pure lime-silicate *wollastonite* is colourless in thin slices, and shows lower refringence and birefringence than the augites. It is further distinguished by having its two principal cleavages and its direction of elongation perpendicular to its plane of symmetry, and consequently giving straight extinction. The *augite* of metamorphosed limestones figures as distinct crystals or crystalline patches, takes part in a finely granular mosaic, or occurs as little globules enclosed in other minerals. The crystals are occasionally twinned on the usual law. The colour is imperceptible in thin slices. The most common amphibole in these rocks is a colourless *tremolite* in imperfect crystals, crystalline patches, veins, or sheaf-like groupings. It may show a fibrous structure or a good hornblende-cleavage, and a rough cross-fracture is also common. Green *hornblende* and blade-like *actinolite* are found in some rocks.

Garnets are highly characteristic minerals of metamorphism, and more than one type is found. The red garnet of metamorphosed argillaceous and arenaceous rocks is an *almandine*, having the ordinary characters. It tends constantly to crystal shape, always the simple dodecahedron, and is often embedded in quartz (fig. 90, *B*). The garnet of metamorphosed limestones is *grossularite*, and likewise makes good crystals (fig. 94). It is often feebly birefringent, and further shows between crossed nicols a polysynthetic twinning of a remarkable kind. With this structure goes a strongly marked zonary banding, the concentric zones differing in birefringence. *Idocrase* occurs

either in well-built crystals or in shapeless plates enclosing other minerals. The cleavage and colour are usually not to be observed in thin sections. The birefringence is variable, and a crystal often shows bands or lamellæ differing in interference-colours. *Zoisite* occurs in little prisms, often grouped in sheaf-like fashion. It is characterized by longitudinal cleavage-traces, high refractive index, low polarization-tints, and straight extinction. *Epidote*, often associated with the last-named mineral, is usually in shapeless grains or granular aggregates, though it may present crystal-boundaries towards calcite, *etc.* The cleavages are well-marked, the two sets of traces intersecting at about 65° in a cross-section. Twinning is uncommon. The larger crystals show the yellow colour and pleochroism. Other distinctive characters are the high refractive index, very brilliant polarization-tints, and straight extinction in longitudinal sections.

A characteristic mineral in metamorphosed dolomite-rocks is the pure magnesian olivine *forsterite*. It forms either crystals of tabular habit (fig. 93) or rounded grains, and by alteration gives rise to serpentine. In certain cases magnesia has crystallized in the form of *periclase*, in octahedra or in rounded grains (*e.g.* in the ejected blocks of Monte Somma, Vesuvius); but this passes readily by hydration into *brucite*, a clear, colourless mineral with one (basal) cleavage, straight extinction with the cleavage-traces, low refringence, and strong birefringence (nearly equal to that of augite).

Among other products of thermal metamorphism in various rocks may be mentioned magnetite and ilmenite, pyrite and pyrrhotite, sphene, rutile and anatase, spinels, corundum, and graphite.

As a special mineral formed in metamorphosed rocks near an igneous intrusion may be noticed *tourmaline*. This mineral occurs in little grains, often in veins which represent cracks, or sometimes very abundantly as a constituent of a kind of contact-breccia. It is restricted to the neighbourhood of acid intrusions, and depends on an actual introduction of certain materials from the igneous magma. White mica has sometimes a similar occurrence; and processes of the same order

Occurs in hornfels of Triassic sediments under Palisade Diabase, New Jersey.

(pneumatolytic metamorphism), operating on impure limestones, have in some cases given rise to *axinite*. Of like significance is the *scapolite* (dipyre) sometimes formed in the metamorphism of calcareous rocks.

Structures. The microstructures of metamorphosed rocks differ essentially from those of igneous rocks, the ruling factor here being the resistance encountered by *crystals growing in a solid medium*. If the rock is composed of a single mineral (*e.g.* a pure limestone or quartzite) its recrystallization results in a simple *mosaic* structure, the individual grains, as seen in a section, having polygonal or slightly interlocking outlines. When different minerals are formed side by side, their mutual relations as regards distinctive shape are determined, not (as in igneous rocks) by sequence of crystallization, but by specific properties of the minerals. Certain 'strong' minerals, such as rutile and garnet, constantly assert their proper crystal-shapes. On the other hand there are 'weak' minerals, such as calcite and quartz, which never show crystal-form in metamorphosed rocks. Between these other minerals can be ranged in a more or less definite order of precedence, and it is found that crystals of a stronger mineral always tend to develop their natural forms at the expense of weaker neighbours.

The peculiar microstructure of metamorphosed rocks results primarily from the struggle between crystals constrained by a solid environment; but many modifications arise from intergrowths and from inclusion of one mineral in another; and another very important factor enters when the recrystallization is effected under unequal stress as well as at high temperatures.

Many of the minerals produced in thermal metamorphism have either a flakey or an acicular habit. When these are developed in a rock possessing a laminated structure, they have some tendency to set themselves in the direction of least resistance, and so to produce a certain parallel structure (fig. 90, *A*). But the parallel orientation is much more pronounced when the recrystallization has been effected under unequal stress, and in the most typical *crystalline schists* this dynamic factor has usually played an important part.

Many sediments present noteworthy differences in mineralogical and chemical composition between different bands or beds, and such differences will naturally be represented by different mineralogical characters of the several bands after metamorphism. In a high grade of metamorphism these differences depending upon original composition may be further accentuated by a process of segregation, particular minerals becoming largely concentrated in lenticular bands and streaks. By these means characteristic *gneisses* may arise in the metamorphism of sedimentary deposits. Rosenbusch termed such rocks 'paragneisses,' as distinguished from 'orthogneisses' which are of igneous origin. He further used the names 'psammite-gneiss' and 'pelite-gneiss' for types arising from the metamorphism of arenaceous and argillaceous sediments respectively.

Metamorphism of arenaceous rocks. The effects of thermal metamorphism in arenaceous rocks are simple or complex according to the homogeneous or heterogeneous nature of the deposits affected. In a pure quartz-sandstone or quartzose grit there are no degrees of metamorphism possible. If the temperature be sufficiently high, the whole will be recrystallized into a clear quartz-mosaic without a trace of the original clastic character. The homogeneous *quartzite* resulting from the complete metamorphism of a pure quartzose rock is not difficult to discriminate from a quartzite formed by the deposition of interstitial quartz. There is no distinction of original grains and cementing material, but each element of the mosaic is clear and homogeneous, presenting an irregular boundary which fits into the inequalities of the adjoining elements. Such quartzites are locally produced in the Skiddaw grits abutting on the large granophyre mass at Ennerdale, in the Carboniferous sandstones near the Whin Sill of Teesdale, and in many other places. If the original sediment contained felspar grains, not much altered, as well as quartz, the felspar is recrystallized with the quartz, and without careful examination is liable to be overlooked in the resulting mosaic. Detrital rutile and tourmaline recrystallize readily, collecting into larger crystals (fig. 92, *B*), and muscovite, in the absence of other impurities, will also recrystallize without change.

Where a quartzose sandstone or grit contains scattered decomposition-products, such as kaolin, calcite, and chloritic minerals, in small quantity, metamorphism produces a quartzite with granules of accessory minerals. Thus, in the grits near the Skiddaw granite chloritic and sericitic matter has given rise to new-formed flakes of biotite; and the grits of the Coniston Flags are transformed near the Shap granite to a quartzite with granules of augite, formed at the expense of chlorite and calcite. In sandstones with ferruginous cement the ferric oxide and hydrate are reduced to magnetite, as is seen in some of the Silurian beds near the granite of New Galloway.

An arkose composed of quartz and abundant fresh felspar presents an interesting case, as illustrated by the Torridon Sandstone near the large ultrabasic intrusions of Rum[1]. The felspar recrystallizes first in slender rods, while the quartz-grains are merely corroded at their surface. At a higher temperature the two minerals recrystallize together in delicate micrographic intergrowth with a tendency to spherulitic structures.

If the original rock was an impure sandstone, containing much aluminous and other substances, the product of metamorphism ceases to have any apparent resemblance to a quartzite. Silicates of alumina, garnet, micas, *etc.*, may be extensively produced, and the metamorphosed rock assumes the aspect of a fine or even a coarse gneiss. Remarkable examples are presented by the Silurian grits and flags round the granites of Galloway[2]. Here the chief constituents are quartz, muscovite, a deep brown biotite, and red garnet (colourless in slices), felspar being only subordinate. The garnets, except at the margin of each crystal, are crowded with minute granular inclusions. Nearer to the granite the texture of the rock becomes coarser, and the muscovite and quartz are seen to be crowded with narrow needles of sillimanite up to ·01 inch long. The same minerals as before are present, with a few crystals of plagioclase and rarely a little brown tourmaline. At a hundred yards from the granite

[1] *Geology of Small Isles* (*Mem. Geol. Sur. Scot.* 1908) 13.

[2] Miss Gardiner, *Q. J. G. S.* (1890) xlvi, 569-580; Teall, *Mem. Geol Sur., Silur. Rocks Scot.* (1899) 644–647.

margin the texture is very coarse, the abundant white mica building plates half an inch in length and relatively thick. Dense matted aggregates of sillimanite needles occupy the interior of the quartz and muscovite, leaving the borders of the crystals clear. Some of the most altered rocks show bands or streaks rich in particular minerals, such as lenticular patches of garnet set in clear quartz or streaks composed essentially of

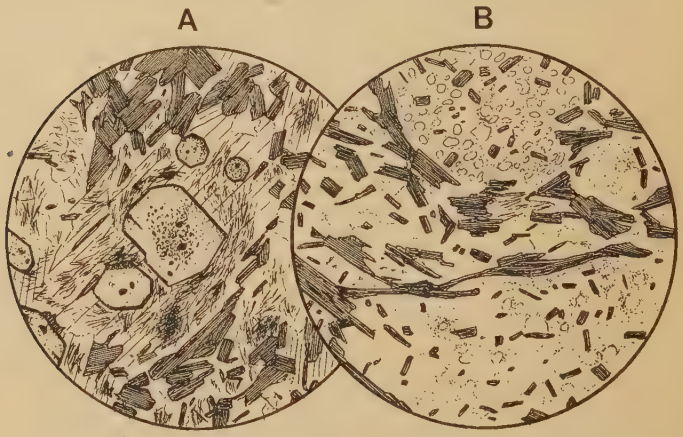

FIG. 89. HIGHLY METAMORPHOSED SEDIMENTS (GNEISSES); ×20.

A. Sillimanite-Gneiss, New Galloway: showing well shaped garnet, biotite, large crystals of muscovite enclosing swarms of sillimanite needles, clear plagioclase, and quartz.

B. Cordierite-Gneiss, Lockwitz valley, Saxony: showing large grains of cordierite enclosing many quartz-granules and flakes of mica: the rest is of quartz and biotite, with some muscovite.

muscovite and sillimanite, dark mica being less plentiful (fig. 89, *A*). These *sillimanite-gneisses* closely resemble others which are associated with crystalline schists in Aberdeenshire and Forfarshire.

The sillimanite formed in such rocks in metamorphism of a high grade is probably a bye-product of the conversion of white mica to felspar. In a grit containing more magnesian

impurities (chlorite, *etc.*) cordierite forms very readily, and in highly metamorphosed sediments gives rise to *cordierite-gneisses*, composed principally of quartz, cordierite, and mica. The distinctive mineral forms irregularly rounded grains or knots with many inclusions of quartz-granules and flakes of biotite (fig. 89, *B*).

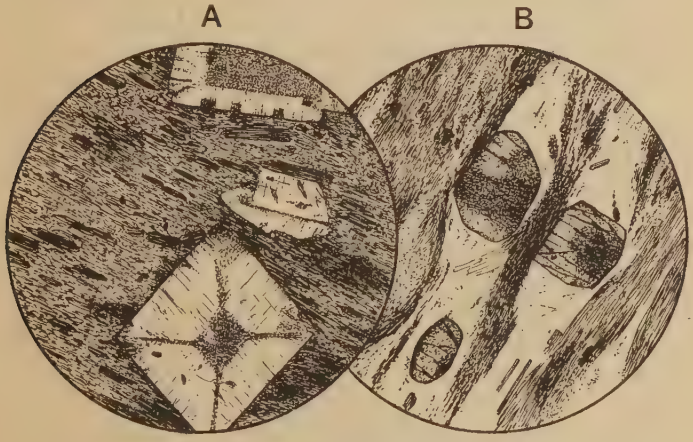

FIG. 90. METAMORPHOSED SLATES; ×20.

A. Chiastolite-slate, Bannerdale. Skiddaw: showing the peculiar arrangement of inclusions in the chiastolite variety of andalusite. Biotite is the only other new mineral visible.

B. Garnetiferous Mica-schist, Blair Atholl, Perthshire: showing garnet crystals, each set in an 'eye' of quartz. Mica has been developed in filmy flakes with parallel arrangement. The rock contains some finely divided graphite.

Metamorphism of argillaceous rocks. In strata containing carbonaceous matter this is one of the first ingredients to suffer change. It is either dissipated and expelled or converted into graphite. The latter is in some cases aggregated into little dark spots, producing one type of what is known as 'spotted slate' (Ger. Knotenschiefer). This peculiarity may be seen in otherwise unaltered strata, and it disappears with

advancing metamorphism. The minute needles of rutile so abundant in slates also seem to be rather readily affected, giving place to stouter crystals of the same mineral. Another early effect of metamorphism is the production of little flakes of brown mica (probably the haughtonite variety of biotite) from chloritic substances, *etc.* With this there may be a crystallization of iron-ores (magnetite or pyrites). In some cases a chloritic mineral or ottrelite is formed instead of the mica. In rocks rich in alumina chiastolite is produced concurrently with biotite, *e.g.* in the Skiddaw district (fig. 90, *A*).

With advancing metamorphism graphitic spots and chiastolite-crystals are lost, and the metamorphism begins to affect the whole body of the rock, the chief products formed being usually quartz and biotite. These rocks may have no trace of the original clastic nature of the deposit, except perhaps some minute angular quartz-grains. They sometimes show a spotted character quite different from that mentioned above, and consisting in little ovoid spaces free, or relatively free, from the flakes of biotite which crowd the rest of the rock. Such spaces often show distinctly crystalline properties, giving extinction parallel with their length, and in many cases, at least, they are ill-developed crystals of andalusite or of cordierite.

In the highly metamorphosed Skiddaw Slates of the Caldew Valley[1], cordierite and andalusite, severally or together, are very abundant. The other common minerals are biotite, muscovite, and in the more siliceous beds quartz; while graphite is usually present, and chlorite, ilmenite, and minute garnets are found in particular beds. When the cordierite occurs in distinct crystal-grains, it gives the well-known 'spotted' appearance, which is also produced in the same way in the metamorphosed Coniston Flags near the Shap granite[2] (fig. 91, *B*). In the Skiddaw Slates these imperfect crystals of cordierite are often complex twins. When, however, the mineral constitutes the chief bulk of the metamorphosed rock, it forms a

[1] *Naturalist*, 1906, 121–123, pl. x, xi; *G. M.* 1894, 169 (cordierite); Rastall, *Q. J. G. S.* (1910) lxvi, 124–139.

[2] Hutchings, *G. M.* 1894, 65. *Cf.* Harker and Marr, *Q. J. G. S.* (1891) xlvii, 320, pl. xii, fig. 5.

sort of ground-mass of irregular grains, fitting together and enclosing biotite and minute garnets. The metamorphosed slates near the Dartmoor granite are often very rich in cordierite[1].

Some highly metamorphosed strata adjacent to plutonic intrusions have a marked schistose character, due to abundant micas of sericitic habit following old structural planes in the

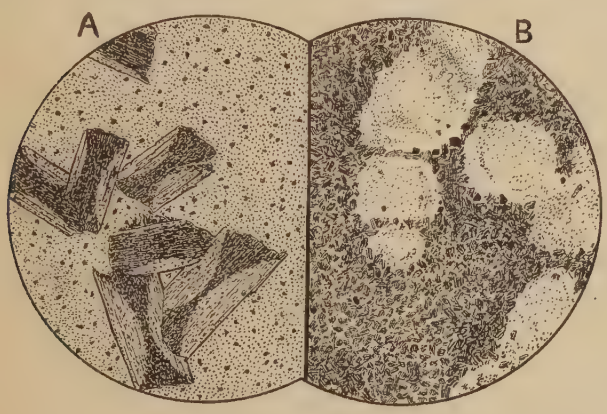

Fig. 91; ×20.

A. Ottrelite-slate (metamorphosed Cambrian slate), Ottré, Ardenne, Belgium. Crystals of ottrelite crowded with inclusions.

B. Cordierite-Mica-schist (metamorphosed Coniston Flags), near Shap granite, Wasdale Beck, Westmorland. The ovoid spaces free from biotite indicate imperfect crystals of cordierite.

rock. The slates near the Leinster granites are in part converted into mica-schists with staurolite and graphite. Locally they show spots, which develop into crystals of andalusite, sometimes of considerable size (Killiney, near Dublin). In the more usual case parallel structure is not marked, and we have merely a compact, fine-textured mass of quartz, micas, iron-ores, *etc.* (Ger. Hornfels, Fr. cornéenne, 'hornstone' of some

[1] *Geology of Dartmoor* (*Mem. Geol. Sur.* 1912) 45.

writers). Andalusite, garnet, *etc.*, characterize different types (Ger. Andalusithornfels, Granathornfels, Biotithornfels, *etc.*). Felspars may be developed in a higher grade of metamorphism, and at the same time the texture becomes coarser, and the rocks acquire the characters of gneisses.

More typical *mica-schists*, as already remarked, are the products of metamorphism involving the dynamic as well as the thermal factor. Dark mica usually predominates, but white is also frequent. Red garnet is common in mica-schists of this kind, and other minerals may occur, according to the original chemical composition of the rock; *e.g.* zoisite, epidote, hornblende, and sphene if the original sediment contained a little calcareous matter. In the highest grades of metamorphism foliation and schistosity become less pronounced, and we have pelitic gneisses, differing from the psammitic in being less siliceous and more micaceous.

Mica-schists are found in great variety in the Highlands of Scotland[1]. Biotite and garnet are the first new minerals to become conspicuous (fig. 90, *B*), or in sediments of more magnesian (chloritic) composition cordierite or chloritoid[2]. With advancing metamorphism other minerals appear, according to the composition of the particular sediments; *viz.* staurolite (fig. 92, *A*), cyanite (fig. 92, *B*), and sillimanite, the last being abundant in many coarse-textured gneissic rocks[3].

In many cases of true contact-metamorphism material introduced into the metamorphosed rocks from an invading magma has given origin to special minerals not dependent wholly on the nature of the strata affected. The commonest of these special minerals is *tourmaline*. It has been formed abundantly in many of the slates bordering the granitic intrusions of Cornwall[4] and Devon. Besides the brown or blue tourmaline, the metamorphosed rocks consist of quartz, micas, chlorite, andalusite, *etc.*

[1] See various *Memoirs* of the Geological Survey.

[2] Barrow, *Q. J. G. S.* (1898) liv, 149–155.

[3] Barrow, *ibid.* (1893) xlix, 343–345; Bosworth, *ibid.* (1910) lxvi, 387–391.

[4] Allport, *ibid.* (1876) xxxii, 408–417; Flett, *Geol. Land's End* (1907) 20–26, and other *Memoirs* of the Geological Survey.

In the neighbourhood of some basic intrusions there seems to have been more important metasomatic change, brought about especially by a transference of soda from the magma to the rocks undergoing metamorphism. Some of the '*adinoles*' of North Cornwall[1], which are Devonian slates metamorphosed by intrusions of albite-dolerite, consist almost wholly of albite.

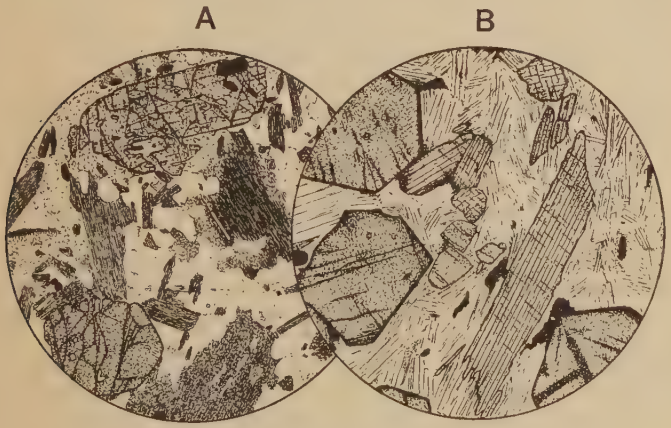

FIG. 92. SCOTTISH CRYSTALLINE SCHISTS; ×20.

A. Staurolite-schist, Glen Clova, Forfarshire: showing large crystals of staurolite (above), garnet (below), biotite with some muscovite, and quartz.

B. Cyanite-schist, Glen Fernate, Perthshire: showing elongated crystals of cyanite, large garnets, some recrystallized tourmaline (centre) and abundant muscovite.

Metamorphism of calcareous rocks. It appears that, under the conditions which rule in ordinary cases of metamorphism by heat, carbonic acid is not driven off from lime-carbonate, except in presence of available silica to replace it. Thus a pure limestone merely becomes recrystallized into a fine- or coarse-grained *marble*, in which all traces of clastic

[1] Fox, *G. M.* 1895, 13–20; McMahon and Hutchings, *ibid.* 257–259; see also *Geology of Padstow* (*Mem. Geol. Sur.* 1910) 48–49.

and organic structures are effaced. This is seen locally in the Mountain Limestone against the Whin Sill of Teesdale, in the purer parts of the Coniston Limestone near the Shap granite, and in numerous other occurrences.

Most metamorphosed limestones, however, have held sufficient impurities to give rise to various lime-bearing silicates, which are found in the recrystallized limestones as crystals, crystalline aggregates, patches, plumose tufts, *etc.* The chief characteristic minerals have been noted above. Two or more of them often occur in association, and sometimes with a regular arrangement. Thus some beds of the Coniston Limestone near the Shap granite enclose large crystals of idocrase in stellate groups or nests, each nest surrounded by a shell composed largely of felspar. The commonest mineral in this mode of occurrence is grossularite, which forms large crystals even in a relatively low grade of metamorphism, *e.g.* in contact with a dyke (Plas Newydd, Anglesey). Wollastonite, tremolite, augite, and epidote are also met with in various associations. Marbles enclosing various silicates are found at numerous localities in the Highland region of crystalline schists. Some in Glen Derry, near the Cairngorm granite, contain aggregates of garnet. In the Glen Tilt rocks we find chiefly amphibole-minerals—tremolite, actinolite, and green or even brown hornblende. A band of crystalline limestone near Tarfside, in the highly metamorphosed area of Forfarshire, has green hornblende, zoisite, felspar, quartz, sphene, and other minerals.

Of special interest is the *dedolomitization* of dolomite-rocks by metamorphism. Here the dolomite is reduced to calcite, while its magnesia enters into new minerals. One well-marked type arising in this way consists of calcite and forsterite (fig. 93), and such a rock may be converted into a serpentinous marble or 'ophicalcite.' Even a pure dolomite-rock, free from siliceous or other impurity, may be dedolomitized; and in this way have been formed the rocks known in the Tirol as 'predazzite' and 'pencatite,' which are granular aggregates of calcite and brucite, the latter probably arising from the hydration of periclase. These and other types are found among the metamorphosed equivalents of the Cambrian dolomite-rocks at

Ledberg in Sutherland, on the border of the Loch Borolan intrusion[1], and also in Skye[2], where the same group of strata is highly metamorphosed by the Tertiary granite and gabbro. The crystalline limestones of Glenelg[3], Tiree[4], and Iona carry a variety of minerals, among which magnesian silicates are well represented, and these rocks must have been in great part dolomitized prior to metamorphism.

The most striking effects, however, are produced in very impure limestones or in calcareous shales, slates, or tuffs. In

FIG. 93. FORSTERITE-MARBLE (METAMORPHOSED CAMBRIAN DOLOMITE), NEAR GRANITE, KILCHRIST, SKYE; ×20.

Showing crystals of olivine (forsterite) in a calcite-mosaic.

these the carbonic acid is completely eliminated, and the whole converted into a *lime-silicate-rock* (the German 'Kalksilikathornfels' or 'Kalkhornfels'). These rocks consist of aggregates, usually very fine-grained and compact, of silicates rich in lime, sometimes with quartz, pyrites, or other minerals. Several of these minerals occur in association, giving rise to rocks of

[1] Teall, *N. W. Highlands* (*Mem. Geol. Sur.* 1907) 453–462.
[2] *Tert. Ign. Rocks Skye* (*Mem. Geol. Sur.* 1904) 145–151.
[3] Clough and Pollard, *Q. J. G. S.* (1899) lv, 372–379.
[4] Coomaráswámey, *ibid.* (1903) lix, 91–103, pl. VI, VII.

complex constitution; and beds differing slightly in the amount and nature of their non-calcareous material result in different mineral-aggregates. Numerous types are illustrated by the metamorphosed Coniston Limestones at Wasdale Head, where they abut on the Shap granite. The Upper Coniston Limestone is extensively converted into a compact porcellanous-looking rock, in which irregular crystalline patches and grains of pyroxenes and other lime-bearing silicates are recognizable.

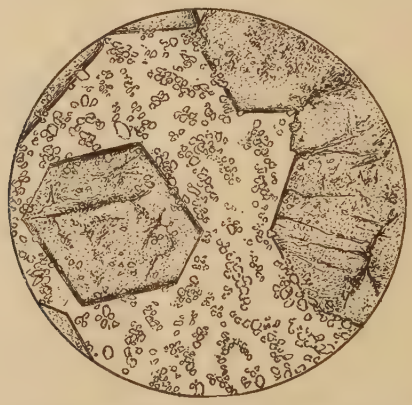

FIG. 94. GARNET-IDOCRASE-ROCK (METAMORPHOSED CONISTON LIMESTONE), NEAR SHAP GRANITE, WASDALE HEAD, WESTMORLAND; ×20.

The highly refringent crystals are the lime-garnet (grossularite), and the clear mineral forming the matrix is idocrase. Both enclose abundant pyroxene-granules.

In some specimens wollastonite predominates, in others augite (omphacite), in others tremolite; and various associations of these and other minerals can be noted in thin slices[1]. Anorthite and probably other felspars are present, sometimes in irregular crystal-plates or patches with ophitic habit, sometimes in minute granules. In the compact rocks are sometimes enclosed stellate groups of large crystals (idocrase or augite), each group

[1] Harker and Marr, *Q. J. G. S.* (1891) xlvii, pl. XII, figs. 3, 4.

surrounded by a shell chiefly of plagioclase crystals[1]. A bed in the Lower Coniston Limestone is converted into a mass of garnet and idocrase. The garnet (grossularite) is in good crystals enclosing pyroxene-granules and enclosed by the clear idocrase[2] (fig. 94). It shows the optical anomalies noted above.

The 'calc-flintas' of the Geological Survey in Cornwall are lime-silicate-rocks representing calcareous bands in the Devonian slates, metamorphosed by the large granite intrusions. They are mostly close-grained rocks, in which quartz, felspar, augite, tremolite, and epidote occur in various associations and relative amounts. Some near Camelford[3] have a more evidently granular texture, and in these garnet and idocrase are the prominent constituents, often crowded with granules of augite.

Bands rich in lime-silicates (including lime-magnesia-silicates) occur among the crystalline schists of the Highlands. In these zoisite and epidote, tremolite and actinolite, are usually the most characteristic constituents, and the formation of these minerals is doubtless promoted by stress-conditions.

Scapolite is found in some metamorphosed limestones, where the pneumatolytic element has entered. Axinite is another mineral occurring in like connection. Mr Barrow[4] has found it, with actinolite and other minerals, in a metamorphosed Devonian limestone at Tregullan, near Bodmin, Cornwall.

Metamorphism of igneous rocks. Although the thermal metamorphism of plutonic rocks, lavas, volcanic ashes, *etc.*, has not yet received very much attention, it offers many points of interest and importance. Basic and sub-basic rocks are, as a rule, much more susceptible to this kind of transformation than acid ones. The most common case is that in which a volcanic series has been invaded and metamorphosed by subsequent plutonic intrusions.

[1] *Q. J. G. S.* (1893) xlix, pl. xvii, fig. 6.
[2] *Ibid.* (1891) xlvii, 311–312, pl. xii, fig. 1.
[3] *Geology of Padstow and Camelford* (*Mem. Geol. Sur.* 1910) 69–72.
[4] *Min. Mag.* (1908) xv, 113–123; *Geology of Bodmin* (*Mem. Geol. Sur.* 1909) 103–104.

The Carrock Fell granophyre, in Cumberland, has produced metamorphism in a very basic type of gabbro. In some examples the apatite and iron-ores are unchanged, the turbid felspars become clear, and the augite is converted into green actinolitic hornblende or into biotite. The latter occurs chiefly near the grains of iron-ores, from which it has probably taken

FIG. 95. METAMORPHOSED DOLERITE DYKE, CLOSE TO GRANITE, KILCHRIST, SKYE; ×20.

The augite is totally transformed to a pale, rather fibrous hornblende, except round the granules and skeletons of iron-ore, where its place is taken by biotite. The felspar crystals have become quite clear, but narrow chloritic veins traversing them have been converted to hornblende.

up some ferrous oxide and titanic acid. Diorites are metamorphosed in the Malvern range, the results, however, being complicated by dynamic changes. As described by Callaway[1], the chief effect clearly referable to heat is the replacement of hornblende by a deep brown biotite in the vicinity of an intruded granite. It appears that the hornblende had been, at least to some extent, previously converted into a chloritic mineral. The plagioclase is stated to give rise to white mica.

[1] *Q. J. G. S.* (1889) xlv, 485, *etc.*

The same author describes the metamorphism of diorite by a granitic intrusion in Galway Bay, where recrystallized plagioclase is observed, and the hornblende has given place to a chloritic mineral, epidote, and rarely biotite.

The metamorphism of dolerites by granitic intrusions has been observed in Cornwall[1] and elsewhere. A series of specimens shows in various stages the conversion of augite into hornblende and the recrystallization of the felspar. The hornblende produced is mostly green, but in the neighbourhood of the iron-ore (ilmenite) it is sometimes brown. Brown mica or scaly patches of chlorite may be found instead of hornblende, and these often give indications of being formed not directly from augite but from its decomposition-products. In the Isle of Skye[2] similar effects are to be observed in dolerite dykes cut off and metamorphosed by the granite of Beinn an Dubhaich (fig. 95).

Near Catacol, in the north of Arran[3], a dyke of vogesite is metamorphosed in contact with the Tertiary granite. Each crystal of hornblende, about $\frac{1}{10}$ inch long, is replaced by an aggregate of biotite-flakes. A pale augite, which was also present in the original rock, shows a like transformation only in an incipient stage. The felspar has undergone recrystallization.

The Tertiary basaltic lavas of Skye[4] are often considerably metamorphosed by the later intrusions of gabbro and granophyre. One interesting result is the formation of felspar in the amygdales. It is produced, together with epidote, zoisite, actinolite, *etc.*, mainly at the expense of soda-lime-zeolites. In the mass of the rock the chief change is usually the conversion of the augite to greenish fibrous hornblende. In the highest grade of metamorphism, however, hornblende is not produced, augite being found both in the body of the rock (recrystallized

[1] Allport, *Q. J. G. S.* (1876) xxxii, 407–427. For figures see Teall, *Brit. Petr.* pl. xvii and xxi, fig. 2.

[2] Harker, *Tertiary Igneous Rocks Skye* (*Mem. Geol. Sur.* 1904) 319.

[3] *Geol. N. Arran* (*Mem. Geol. Sur. Scot.* 1903) 109.

[4] Harker, *Tertiary Igneous Rocks Skye* (1904) 50–53, pl. xvii, figs. 4, 5, and xviii, fig. 1. See also McLintock, *Tr. Roy. Soc. Edin.* (1915) li, 25–29, pl. iii (Mull).

in common with the felspar) and in the amygdales (associated with new felspar which replaces zeolites).

The augite-andesites on the west side of the Shap granite[1] afford fine examples of thermal metamorphism. They had undergone considerable change prior to the post-Silurian intrusion of the granite. Chloritic minerals, calcite, chalcedony,

FIG. 96. METAMORPHOSED BASIC LAVA ENCLOSED IN THE GABBRO OF CARROCK FELL, CUMBERLAND; ×20.

The rock was originally a hypersthene-basalt belonging to the Eycott Hill group (see fig. 64, *A*). The porphyritic felspars have become clearer (*lb*), their large inclusions disappearing; the pyroxenes or their weathering-products have been converted chiefly into a pale hornblende (*hb*) or locally into biotite (*bi*); the magnetite has recrystallized in good octahedra; and the felspars of the ground-mass are now a clear aggregate, which appears almost homogeneous in natural light.

and quartz had been formed from the pyroxene and felspar, and were partly disseminated through the rock, but especially collected in little veins and in the vesicles. These alteration-products were the elements most readily affected by heat. The chloritic mineral has been converted into biotite, or, where it

[1] Harker and Marr, *Q. J. G. S.* (1891) xlvii, 294–300.

was associated with calcite, into green hornblende (notably in the vesicles): chalcedonic silica has been transformed into crystalline quartz. The rocks are more altered nearer the granite, and new minerals appear, such as a purplish brown sphene, magnetite, and pyrites; the plagioclase phenocrysts are replaced by a mosaic of new felspar-substance; and finally the whole mass of the rock is found to be reconstituted, the ground becoming a fine-textured mosaic of clear granules. Kynaston[1] has described similar effects in the Old Red Sandstone andesites bordering the Cheviot granite.

A more basic type of lava, on the north side of the Shap granite, shows phenomena on the whole very similar to the preceding; but, owing to the larger percentage of lime present, the minerals produced are in part different. Green hornblende predominates over biotite among the coloured constituents of the metamorphosed rocks, and an augite, colourless in slices, is also formed, especially in veins and amygdales. Epidote is another characteristic mineral, and sphene, pyrites, and magnetite occur as before. Especially noteworthy is the formation of numerous lime-bearing silicates from the contents of the vesicles: grossularite occurs, as well as hornblende and actinolite, epidote, augite, and quartz. In the centre of the largest amygdales some residual calcite is found, recrystallized but not decomposed[2]. A basic hypersthene-bearing lava (the Eycott type) is metamorphosed by the Carrock Fell gabbro[3], the bastite pseudomorphs after hypersthene being converted into a pale hornblende. Here the transformation of the rocks is not always complete, the large labradorite phenocrysts being, as a rule, not recrystallized into a mosaic, but only cleared of their dusty inclusions (fig. 96). The metamorphosed Ordovician lavas near the Galloway granites[4] recall in many respects the Shap rocks. A lime-garnet is frequently met with, and new felspar occurs both in the body of the rock and in the amygdales.

[1] *Tr. Edin. G. S.* (1901) viii, 18–26.
[2] *Q. J. G. S.* (1893) xlix, 360–364, pl. xvii, figs. 1–4.
[3] *Ibid.* (1894) l, 332.
[4] Teall, *Ann. Rep. Geol. Sur.* for 1896, 47; *Mem. Geol. Sur., Silur. Rocks Scot.* (1899) 647–650.

The rhyolites near the Shap granite do not, as a rule, show any changes that can be clearly attributed to the effects of heat. Where, however, decomposition-products existed in the original rocks, they have given rise to metamorphic minerals. In particular, the green pinitoid substance is converted into a mixture of white and brown micas.

CHAPTER XXIII

DYNAMIC METAMORPHISM

In this chapter will be noticed some of the principal changes induced in rocks of various kinds when subjected to powerful mechanical stress at low or moderate temperatures. Two types of stress are to be distinguished, *viz.* equal or 'hydrostatic' pressure and shearing stress; and the actual stress at any point within a rock-mass can always be resolved into a superposition of these two types. Of the two, shearing stress is by far the more important.

The consideration of dynamic metamorphism in comparatively yielding rock-masses has already been partly anticipated in the chapter devoted to argillaceous sediments: phenomena more striking, or at least more easily investigated, are now to be noticed in crystalline and other rocks of more stubborn consistency. The changes to be remarked include those which are purely mechanical and those which involve chemical reactions, and so give rise to new minerals. Of the former kind are the deformation and fracture of the component crystals of a rock and displacement of their relative position. The setting up of schistose and foliated structures is only in part of this kind: it involves mineralogical transformations in addition, and this is true even of the cleavage-structure of ordinary slates (p. 218). Many minerals, of igneous rocks especially, cease to be stable when subjected to shearing stress at low temperatures, and give rise accordingly to other products. In metamorphism of the most general kind, here excluded, high temperature and shearing stress are co-ordinate conditions controlling all mineralogical transformations. Equal pressure is a factor of much less importance: in so far as it is effective, it promotes any change which is attended by diminution of total volume. It thus favours the formation of dense minerals, such as garnet, in rocks crystallized under deep-seated conditions (compare eclogite, p. 82).

Strain-phenomena in crystalline rocks. A frequent effect of strain in the component crystals of a stubborn rock-mass is a modification of the optical properties, which at once

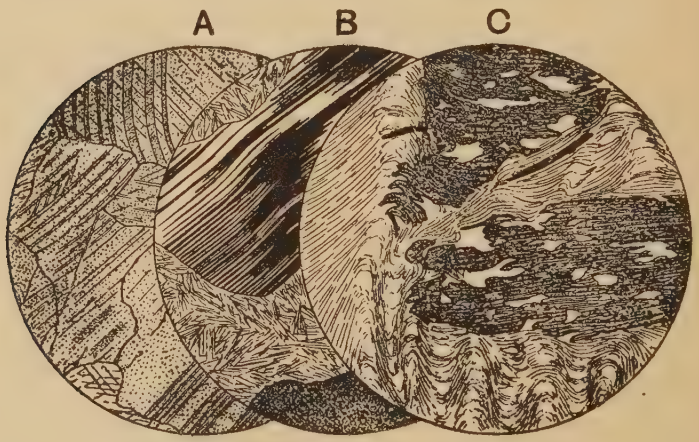

FIG. 97. STRAIN- AND CATACLASTIC EFFECTS.

A. Secondary twin-lamellation in calcite; ×20; in crystalline limestone, Mt Gendres, Pyrenees.

B Secondary twin-lamellation in plagioclase felspar; ×20, *crossed nicols*: in gabbro, Pen Voose, Lizard, Cornwall. The matted fibrous aggregate is actinolite, replacing diallage.

C. Crushed Staurolite-Mica-schist, Lukmanier Pass, Lepontine Alps; ×13. Here a rock already in the condition of a crystalline schist has been subjected to further stress. The staurolite crystals have been shattered, and the foliation-surfaces, marked by the arrangement of the mica-flakes, have been thrown into minute folds. Clear quartz occupies the loops of the folds, as well as the crevices made by the fracture of the staurolite crystals.

becomes apparent between crossed nicols. Instead of being dark throughout for certain definite positions, a crystal shows dark shadows which move across it as the stage is rotated, owing to the directions of extinction varying from point to

point. These *strain-shadows*[1] are best seen in quartz, and are very common in the granitic and gneissic rocks, quartzites, *etc.*, of countries like the Scottish Highlands.

Flexible minerals, such as micas, often show *bending* of their crystals, or, again, have yielded by a shearing movement, analogous to lamellar twinning, parallel to definite directions known as *gliding-planes* (fig. 97, *A*). In some minerals, such as the plagioclase felspars, the gliding-planes coincide with natural twin-planes[2], and the *secondary twinning* can be distinguished from original lamellation only by its inconstant character and its relation to bending or other strain-phenomena (fig. 97, *B*). Sometimes, in one crystal, the closeness of the secondary lamellæ is seen to increase with the strain, until the crystal has yielded along a crack or a granulated vein.

Quartz sometimes shows *rows of fluid-pores* marking directions of shearing-strain, and perhaps parallel to actual planes of faulting if the crystal has yielded[3]. The lines of pores may be traceable through contiguous crystal-grains; or entering another mineral, such as felspar, they may become actual planes of discontinuity.

Judd has maintained that the *schiller-structures*[4], so characteristic of certain minerals in deep-seated rocks, may be produced as secondary phenomena by pressure. A typical structure is that in which cavities of definite form and orientation ('negative crystals') are developed along certain planes, and filled, or partially filled, by material dissolved out from the enclosing crystal. Hypersthene affords a good example (fig. 22, *A*). The 'solution-planes' (Ger. Lösungsflächen) proper to a mineral are parallel to one or more crystallographic planes; but after a secondary lamellar twinning has been set up in a crystal, the gliding-planes become the easiest solution-planes. Pyroxenes, felspars, and olivine are minerals often affected by schiller-structures.

[1] Mr Blake styled this appearance 'spectral polarization.' It is spoken of by some foreign writers as 'undulose extinction.'

[2] Judd, *Q. J. G. S.* (1885) xli, 363–366, pl. x, fig. 1.

[3] Judd, *Min. Mag.* (1886) vii, 82, pl. III, fig. 1.

[4] *Q. J. G. S.* (1885) xli, 374–389, pl. X–XII; *Min. Mag.* (1886) vii, 81–92, pl. III.

Crystals of brittle minerals subjected to stress have often yielded by actual *cracks*, which may have a definite direction throughout the rock, being perpendicular to the maximum tension, and so parallel to the maximum pressure. This is sometimes seen in quartz and felspars, but most commonly in

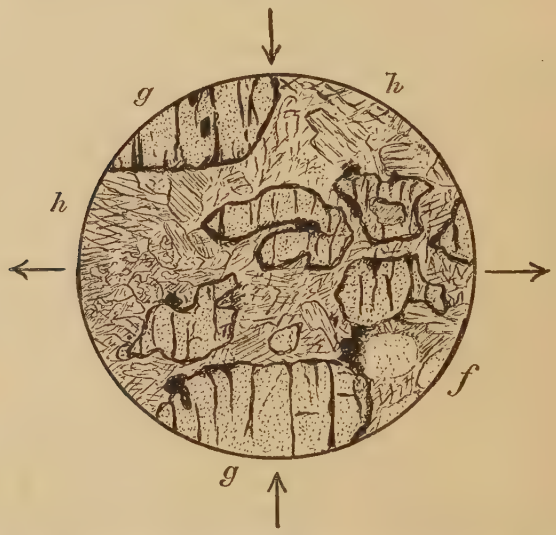

Fig. 98. Hornblende-eclogite (garnet-amphibolite), Loch Laxford, Sutherland; × 15.

Consisting of red garnet (*g*) and green hornblende (*h*), with only a little clear quartz, turbid felspar (*f*), and opaque iron-ore. The arrows show the direction of the stresses that have operated in the rock, and the brittle garnets are traversed by a strongly marked system of cracks perpendicular to the direction of tension.

garnet (fig. 98). As a further stage, the portions of a fractured crystal may be separated and rolled over, or drawn out in the direction of stretching or flowing movement. The tension-cracks are necessarily perpendicular to any schistosity which may be set up in the deformation of the rock.

Cataclastic structures. The phenomena of internal fracture and crushing of hard rocks ('cataclastic' structures of Kjerulf) are to be seen in endless variety in some regions of great mechanical disturbance. They may be developed in less or greater degree; they may affect some or all of the mineral constituents of a composite rock; they may or may not tend to a parallel arrangement of the elements. In one type the rock-mass breaks up along definite surfaces of sliding, the material bordering the cracks being often ground down by friction: this is *brecciation in situ.* The irregularly intersecting surfaces divide the rock into angular fragments; but these may be rolled over and their angles rubbed off, so that a 'friction-conglomerate' as well as a 'friction-breccia' may arise, especially along faults and thrust-faults (*e.g.* Lake District). According as the new structure is on a large or a small scale, the fragments may be recognizable pieces of rocks or portions of constituent crystals of an originally crystalline rock.

Again, we sometimes find the larger elements of a rock—grains of quartz, crystals of felspar, *etc.*—surrounded by a border of finely granular material furnished by the grinding down of the crystal itself and adjacent ones. This is the *morter-structure* (Ger. Mörtelstructur) of Törnebohm. As a further stage, the finely granular portion of the rock may make up the chief part of its bulk, forming a matrix which encloses portions of crystals not destroyed but indicating by irregular polarization their strained condition (figs. 99, *C* and 100).

In many cases mechanical forces having a definite direction have caused uncrushed fragments to assume an eye-shaped or *lenticular* form (Ger. Augenstructur) with their long axes perpendicular to the maximum pressure, and so parallel to one another and to any schistose structure in the matrix (figs. 99, *A* and 100). In such cases the crushed matrix usually has a more or less well-marked parallel structure or *schistosity*, in part analogous to slaty cleavage. The final result of the grinding down and rolling out processes is the type of rock named *mylonite* by Professor Lapworth, in which, except perhaps for occasional uncrushed 'eyes,' all original structures are lost.

In these much-crushed rocks the 'eyes' represent in many cases porphyritic crystals, usually of felspar, in what was once an ordinary igneous rock. In the absence of such indications, it is often impossible to determine by microscopical study alone the nature of a rock whose original structures have been totally obliterated.

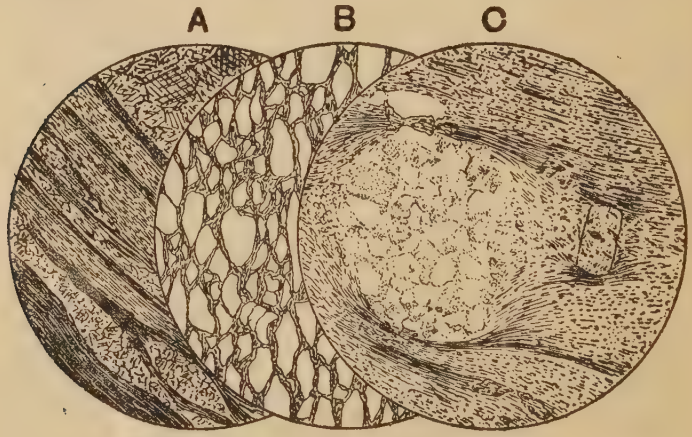

FIG. 99. CATACLASTIC EFFECTS.

A. Crushed Limestone, Devonian, Ilfracombe; ×20. With unbroken 'eyes': part of one is shown in the upper part of the field, and smaller ones in the lower part.

B. Schistose Grit, North Glen Sannox, Arran; ×13. Showing parallel orientation of quartz-grains.

C. Crushed Quartz-porphyry dyke, Dhoon, Isle of Man; ×13. With an 'eye' of rock which has escaped crushing.

Mineralogical transformations. In the crushing of crystalline rocks the changes produced are by no means purely mechanical. In consequence of the stress and subsequent relief a *recrystallization* of minerals may be effected, resulting in the clear, finely granular aggregate which forms a large part of some dynamo-metamorphic rocks. This *granulitization* is often observable as a crush-effect in rocks composed essentially of felspars and quartz, and there is no reason to suppose that

high temperature is essential to its production. It is distinguished from any merely mechanical effect of crushing by the manner in which the component clear granules fit together, giving a mosaic structure. Here no chemical reaction is implied, but in general atomic as well as molecular rearrangement has operated in greater or less degree in any dynamo-metamorphic rock not of the simplest constitution. Certain *mineralogical transformations* seem to be characteristic of dynamic metamorphism, being either developed by the action of great stress, or at least facilitated by stress even when they can also take place without that condition. It should be noticed that in crystalline, and generally in hard, rocks, these mineralogical changes begin before any important structural modifications are produced.

One characteristic change is the production of colourless mica at the expense of potash-felspars. The mineral may be formed at the margin of a crystal squeezed against its neighbours or on surfaces of lamination or of movement in a felspathic rock: in such cases it takes the filmy form known as *sericite* (fig. 99, *C*). Nepheline under like conditions also gives rise to a sericitic aggregate.

A characteristic alteration in the soda-lime-felspars results in the minutely granular aggregate which has been called '*saussurite*,' and is not always of precisely the same nature[1]. The soda-bearing silicate of the felspar separates out as very minute clear crystals of albite, while the lime-bearing silicate, in conjunction with other constituents of the rock, goes to form minerals rich in lime. Zoisite is a characteristic product, or its place may be taken by yellow or colourless epidote; and needles of actinolite may also occur, often accompanied by calcite.

Augite commonly gives rise when crushed to chlorite and calcite. The conversion of augite or other pyroxenes into green hornblende is also a common feature in regions of dynamic metamorphism, but it is certain that at low temperatures *chloritization*, not uralitization, is the normal transformation, and hornblende likewise becomes chloritized.

[1] Teall, *Brit. Petr.* (1888) 149–152; Hyland, *G. M.* 1890, 205–208; G. H. Williams, *Bull.* 62 *U. S. Geol. Sur.* (1890) 58–60. 68–69, figures.

Other changes common in dynamic metamorphism are the conversion of olivine into tremolite or anthophyllite and talc, and the production of granular sphene at the expense of ilmenite or other titaniferous minerals. Melanite also gives rise to sphene and magnetite. The scaly form of serpentine known as antigorite is characteristic of dynamic metamorphism, and may be formed either from ordinary serpentine or directly from olivine.

The borders ('reaction-rims') sometimes noticed at the junction of two different minerals in a crystalline rock have in many cases been attributed to dynamic metamorphism. In particular a ring of garnet crystals may be formed by reaction between a lime-bearing felspar and a pyroxene.

Illustrative examples. It is the calcareous and the siliceous rocks that best illustrate dynamic metamorphism of the purely mechanical kind, not complicated by chemical reactions. Limestones and dolomites may acquire a very perfect slaty cleavage, as is well illustrated in the Devonian of Devonshire. Sorby[1] showed that this is connected with the crushing of the rocks, the individual grains of which they are now composed having their longer axes generally parallel to the plane of cleavage. This is due partly to rotation and partly to deformation of fragments; but the visible structure in thin slices shows that much recrystallization has also taken place under the influence of unequal stress. Sorby pointed out that any individual element of the rock tends to suffer solution on those parts of its surface which bear the greatest stress, with concurrent redeposition on those parts where the stress is least; and this must lead to a gradual flattening in the plane perpendicular to the maximum pressure. Some of the well cleaved limestones near Ilfracombe have a microscopic 'eyed' structure, owing to the preservation of uncrushed lenticles of the original rock (fig. 99, *A*).

Crystalline limestones which have suffered powerful mechanical disturbance constantly show cataclastic and strain-phenomena (fig. 97, *A*). These take the form of curvature of

[1] *Phil. Mag.* (4) xi (1856) 20–37; *Q. J. G. S.* (1879) xxxv, *Proc.* 87–89

the calcite crystals, gliding-planes, and finally granulitization and recrystallization. Interesting effects are observed in metamorphic marbles which enclose crystals of various silicates harder and more resistant than the calcite. The marbles of Tiree[1], in the Hebrides, afford good examples. They show granulitization in various stages, but the enclosed crystals of augite and felspar, though bent and showing gliding-planes, have not been crushed. They are sometimes seen as 'eyes'[2] in

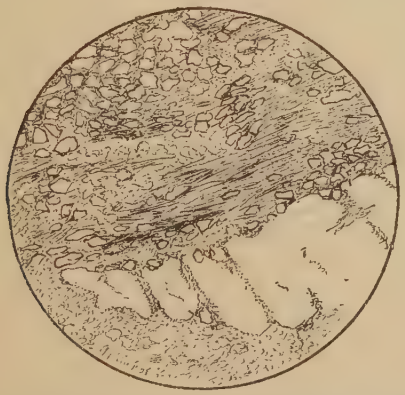

FIG. 100. ADVANCED CATACLASTIC STRUCTURE IN GNEISS, SOUTH SLOPE OF BEINN MÒR OF ASSYNT, SUTHERLAND; ×20.

The greater part of the rock is completely broken down, and has partly taken on the parallel structure of a mylonite. A large grain of quartz is only partly crushed, and this between crossed nicols shows strain-shadows.

a fine-textured and partly schistose matrix, while in the corners of the eyes relics of the original coarse-grained marble remain, protected by the hard crystals.

Quartzose sandstones or grits may acquire a rude schistose structure (fig. 99, *B*), either by an enforced parallel arrangement of the grains or as a result of actual crushing. The

[1] Coomáraswámey, *Q. J. G. S.* (1903) lix, 91–103.
[2] Bonney, *G. M.* 1889, 485.

quartzites of Sutherland in the neighbourhood of the great overthrusts show all the usual cataclastic effects, including strain-shadows in the uncrushed relics. The Lewisian gneisses under like conditions exhibit similar phenomena, but here mineralogical changes have also supervened, especially sericitization along surfaces of shearing movement (fig. 100). This is generally the most conspicuous feature in all acid igneous rocks which have undergone dynamic metamorphism. In porphyritic rocks eyed structures are very common (fig. 99, *C*). Quartz-porphyries in disturbed areas often have a rough schistosity, which is accentuated by films of 'sericitic' mica, formed at the expense of the felspar. The rock of Sharpley Tor in Charnwood Forest is a good example. Similar features are shown by the Llanberis mass of quartz-porphyry at numerous points on its south-eastern edge, especially near Llanllyfni.

The nepheline-syenites of Assynt, and especially the Borolan type (p. 59), are in many places strongly affected by shearing. The orthoclase breaks up into a mosaic of smaller crystal-grains. The nepheline is more easily destroyed, giving rise to an aggregate in which minute scales of white mica are the principal element. Granular sphene is produced at the expense of the melanite[1], and the biotite is replaced by chlorite. In the final stage the rock has become a mylonite with much sericitic mica and only residual 'eyes' of felspar, while magnetite and green chloritic matter represent the destroyed ferro-magnesian minerals[2].

The dynamic metamorphism of basic igneous rocks may be studied in the disturbed belts of the North-West Highlands and elsewhere. Augite is the first of the chief constituents to be destroyed, giving sometimes a felspar-chlorite-schist; while the final stage is a chlorite-schist containing no felspar other than secondary albite, but often having epidote and always more or less of the carbonates (calcite, dolomite, chalybite). It appears that hornblende-schists are produced only under the influence of high temperature as well as shearing stress; but the hornblende-schists themselves may become chloritized by

[1] Shand, *Tr. Edin. Geol. Soc.* (1908) ix, 205–206
[2] *Ibid.* (1910) ix, 409–410.

subsequent crushing[1]. The 'Green Schists' of the Highland Border in Forfarshire represent partly ophitic dolerites, partly spilitic lavas. The spilites of Cornwall and Devon, when sheared, show the same mineralogical changes, resulting finally in a calc-chlorite schist with secondary quartz, limonite, and residual albite. The rocks known as 'schalstein'[2] have originated in this way, but include altered spilitic tuffs as well as lavas.

The dynamic metamorphism of ultrabasic rocks is well illustrated by sheared peridotite dykes in the neighbourhood of Loch Assynt and Lochinver, in West Sutherland. The chief mineral formed is pale amphibole in fibrous patches and aggregates of little needles: it is mainly tremolite but in part the rhombic anthophyllite. Talc is seen in slices as aggregates of minute scales with the high polarization-tints of muscovite but a lower refractive index, and serpentine is also present. Carbonates (dolomite and chalybite) often occur in rather large rhombs.

[1] *Geol. Structure N.W. Highlands* (*Mem. Geol. Sur.* 1907) 209, 241–242.
[2] Flett, *Geology of Plymouth and Liskeard* (*Mem. Geol. Sur.* 1907) 94–95.

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